Astron. Astrophys. 317, 244–247 (1997)

ASTRONOMY
AND
ASTROPHYSICS

On Hα source function vertical variations in filaments and bright rims visibility

Frédéric Paletou*

[1] Institut d'Astrophysique Spatiale, Université de Paris XI, Bâtiment 121, F-91405 Orsay Cedex, France
[2] Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029, Blindern, N-0315 Oslo, Norway

Received 5 December 1995 / Accepted 15 May 1996

Abstract. Using new radiative modelling capabilities in two-dimensional (2D) cartesian geometry, we investigate the vertical variations of the Hα source function in filaments. It is shown how the two-dimensional geometry can affect the transfer of the Hα line into filaments and, consequently, how assumptions on the geometry of the model may influence a further interpretation of observations. A special attention is paid to the possibility of formation of a bright rim inside the filament body by diffusive penetration of Hα radiation. Unlike recently proposed by Heinzel et al. (1995), we can see from our 2D computations that the observable emergent intensities are not high enough to explain bright rims contrasts.

Key words: radiative transfer – Sun: prominences – Sun: filaments

1. Introduction

Filament and prominence diagnostics are based very often on Hα observations made at very high spatial, spectral and temporal resolution. Since this line is generally optically thick in these structures, non–LTE radiative transfer is necessary to accurately interpret the collected Hα emission.

So far, most of the modelling of the hydrogen spectrum of prominences has been performed using vertically standing mono-dimensional (1D) slabs of finite size symmetrically illuminated by the solar surface underneath. The most recent of such studies was carried out by Gouttebroze et al. (1993) who computed a set of 140 non–LTE models of prominences. From their modelling results, the same authors (Heinzel et al. 1994) could derive several interesting theoretical correlations between plasma parameters and the emitted radiation. However, these results are relevant only to observations of prominences as seen above the limb. Besides, the nature of the geometrical problem in 1D makes it impossible to derive any self-consistent vertical variations of observable quantities.

Concerning observations of prominences as seen on the disk i.e. filaments, in 1D geometry one should use *horizontal* slab models in order to evaluate emergent intensities. But with such slabs, even though the vertical variations of, for instance, the source function of a given transition can be evaluated, it is by nature impossible to determine vertical variations of the emergent intensity for lines of sight normal to the structure. Furthermore, 1D horizontal slabs strongly irradiated from below are a priori likely to trap too much radiation since they do not provide realistic photon escape paths.

More realistic filament and prominence models definitely need to solve non–LTE radiative transfer problems for multilevel atoms in at least two-dimensional (2D) geometry. An obvious feature of 2D models is the possibility of taking into account *(i)* more external illumination and *(ii)* more photon escape possibilities across the boundaries. Emergent intensities can be computed in all directions and, vertical and horizontal variations of the emitted radiation can be properly evaluated unlike in 1D geometry. Recent developments in the field of 2D non–LTE radiative transfer make it possible to perform more realistic modelling of isolated and illuminated structures in the solar atmosphere (Auer & Paletou 1994; Paletou et al. 1993). Moreover, numerical techniques described in Paletou (1995) for the solution of 2D multilevel radiative transfer problems including the effects of partial frequency redistribution are very relevant to filament and prominence modelling.

In this article, the effects of 2D radiative transfer on the vertical variations of the Hα source function are discussed. A special attention is paid to the problem of bright rims of filaments and their visibility. This feature of filaments has been frequently observed for decades (d'Azambuja & d'Azambuja 1948) but its explanation still remains unclear. Concerning its interpretation, it was lately proposed by Heinzel et al. (1995) that bright rims of filaments may result from pure radiative transfer effects leading to an enhancement of the Hα source function, S(Hα), at the filament bottom. This tentative explanation had the merit of considering that the bright rim is a natural part of the filament.

Send offprint requests to: paletou@obs-nice.fr
* Present address: Observatoire de la Côte d'Azur, Laboratoire G.D. Cassini, B.P. 229, F-06304 Nice Cedex 4, France

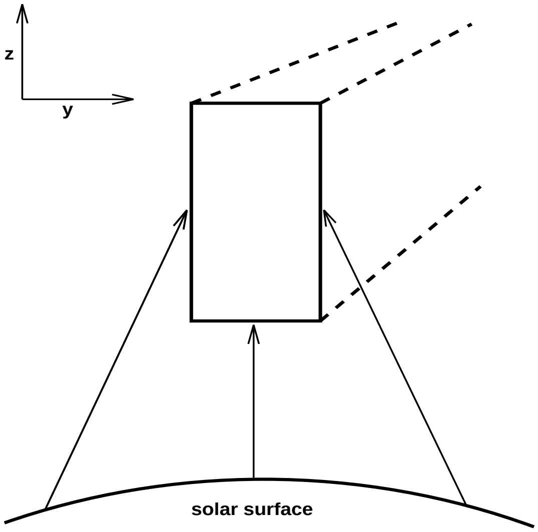

Fig. 1. Geometrical model of a 2D freestanding slab in the solar corona and illuminated from below by the solar surface. The slab is infinite in the direction of the dashed lines. On the bottom boundary, the incident radiation is almost undiluted while it is diluted as a function of the altitude on the sides. We do not consider any illumination from above

Yet, their study suffered from being restricted to a 1D horizontal slab model geometry.

Based on 2D radiative modelling, we demonstrate how Heinzel et al. (1995) explanation of the nature of bright rims proves to be insufficient. More generally, it illustrates some of the limitations of assuming a 1D geometry for the modelling of isolated and illuminated solar atmospheric structures.

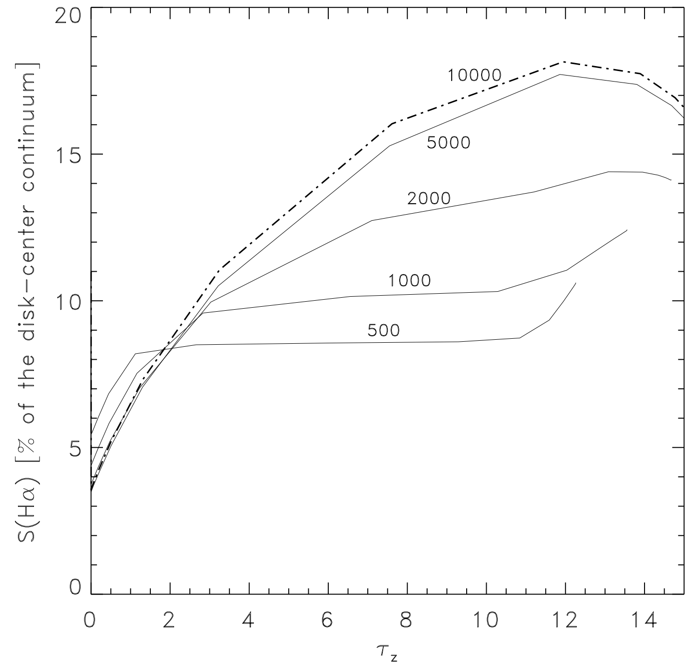

Fig. 2. Vertical variations of the Hα source function along the symmetry axis of the 2D slab. The height scales as the optical depth at line center computed downwards from the top boundary. Each curve is labelled with the corresponding slab width value. The dash-dotted line (D_y=10 000 km) reproduces almost exactly the S(Hα) variations computed in 1D. In most parts of the filament, the source function and the total optical thickness τ_0 at line center decrease with the slab width. For D_y=500 km, the source function is almost constant ($\approx 8\%$) except at the boundaries

2. Non–LTE models

Fig. 1 shows the geometry of the model. The 2D freestanding slab is hanging in the corona and strongly irradiated on its sides and bottom by the solar surface underneath (we do not consider any coronal illumination). The slab is homogeneous and static, standing at a height h = 10 000 km above the solar surface. Its vertical *geometrical* extension is fixed at D_z = 3 200 km which is equivalent to the height of the 1D slab adopted by Heinzel et al. (1995). However, we shall vary its horizontal extension D_y by adopting the respective widths: 500, 1 000, 2 000, 5 000 and 10 000 km. According to Heinzel et al. (1995), other input parameters such as the kinetic temperature T = 8 000 K, gas pressure $p_{\rm g}$ = 0.3 dyn cm^{-2} and the microturbulent velocity ξ = 5 km s^{-1} are the same for any of the five models.

We consider a 5 level plus a continuum hydrogen atom model. A fraction of neutral helium atoms with the abundance relative to hydrogen $\alpha_{\rm He}$ = 0.1 is also included. Partial frequency redistribution (PRD) effects which play an important role in the formation of strong resonance lines in prominences (Heinzel et al. 1987; Paletou et al. 1993) are also taken into account. Therefore, Lyα and Lyβ resonance lines are treated in PRD and other lines are formed in complete frequency redistribution. The Lyman continuum, in general optically thick, is explicitly evaluated while other continua are treated in the optically thin approximation (the latter is indeed valid for subordinate continua).

Numerical strategies for the solution of the 2D non–LTE radiative transfer problem are presented in Paletou (1995). The definition of the incident radiation for each transition is described in details in Gouttebroze et al. (1993) and Paletou (1996).

3. Vertical variations of S(Hα)

When adopting these physical parameters, atomic model and incident radiation, we recover from a 1D horizontal slab model of geometrical extension D_z the same Hα source function vertical variations as obtained by Heinzel et al. (1995). For this model, the vertical column mass is m = 1.35 × 10^{-4} g cm^{-2} and the total optical thickness τ_0 at Hα line center is 15.

As shown in Fig. 2, where S(Hα) is plotted as a function of the line center optical depth computed inward from the top boundary, the same variations as in 1D (the dot-dashed curve) are recovered along the vertical axis of symmetry of the 2D model which has the largest horizontal extension (10 000 km). S(Hα) is expressed in units of the nearby disk-center continuum intensity (4.077 × 10^{-5} cgs). As reported in Heinzel et al. (1995)

computations, from the top of the slab to the bottom S(Hα) varies from 4% to 16%. A maximum value of the order of 18% is reached at optical depth 11.5 and the source function exceeds 13% (the Hα line center intensity close to the limb) for $\tau_z > 5$. Indeed, the horizontal optical thickness is yet large enough to minimize lateral transfer effects on the innermost parts of the slab, far from the vertical boundaries.

It was further argued that the possible excess of S(Hα) at the bottom regions of the slab could explain the existence of a bright rim due to the diffusive penetration of the chromospheric Hα radiation into the structure. Given the above-described Hα source function vertical variations, it was then inferred by Heinzel et al. (1995) that the bottom regions of the filament seen close to the limb could scatter more than the 13% value of the chromospheric emission along lines of sight almost parallel to the solar surface (the Hα line center intensity of the quiet chromosphere drops from approximately 16% at disk center to 13% close to the limb). Therefore a line center intensity excess of the order of 4% relative to the chromosphere could be achieved and could explain the observation of a bright rim in Hα. Also in that scenario and unlike other possible explanations of this phenomenon, the bright rim happens to be a natural part of the filament body.

However, for smaller geometrical slab widths and accordingly horizontal optical thickness, lateral radiative transfer effects do "increasingly" affect the whole slab. This is shown in Fig. 2 where S(Hα) as a function of τ_z is displayed for different values of D_y (the solid lines). For decreasing widths, the Hα source function decreases almost everywhere in the filament body; only top values may increase by a few percent compared to the largest width model. The total vertical optical thickness τ_0 remains large for all models. Hence, for the lowest width model of moderate lateral optical thickness ($\tau_y \lesssim 2$) we finally reach the limit of S(Hα)≈8% throughout most of the slab. Indeed, as stated in Heinzel et al. (1994), the Hα source function in prominences is driven by resonance scattering of the incident solar radiation with a (quiet sun) line center intensity of about 16% and a dilution factor of the order of $\frac{1}{2}$.

It should be noticed also that source function values of 7–8% of the nearby disk-center continuum intensity obtained at optical depth unity are comparable to commonly observed Hα line center emergent intensities of filaments as seen on the disk. Electron densities are also in the range of commonly accepted values for these structures ($n_e \approx 10^{10-11}$ cm^{-3}).

Finally, given the possibility of having Hα source function values exceeding 13% at some regions of the slab, an important question not answered by Heinzel et al. (1995) concerns the visibility of such effect. In other terms, we are also interested in knowing the *geometrical extension* of that portion of the filament and, consequently, if it is any observable.

4. Vertical variations of the Hα emergent intensity

Contrary to 1D horizontal slab models, we can evaluate the intensity emerging along lines of sight normal to the filament. Then, we can relate the vertical variations of S(Hα) to the relative brightness of the structure as seen close to the limb. 2D results are displayed in Fig. 3 where the emergent *line center* intensity, I$_c$(Hα), is plotted against the vertical extension of the slab in arcsec.

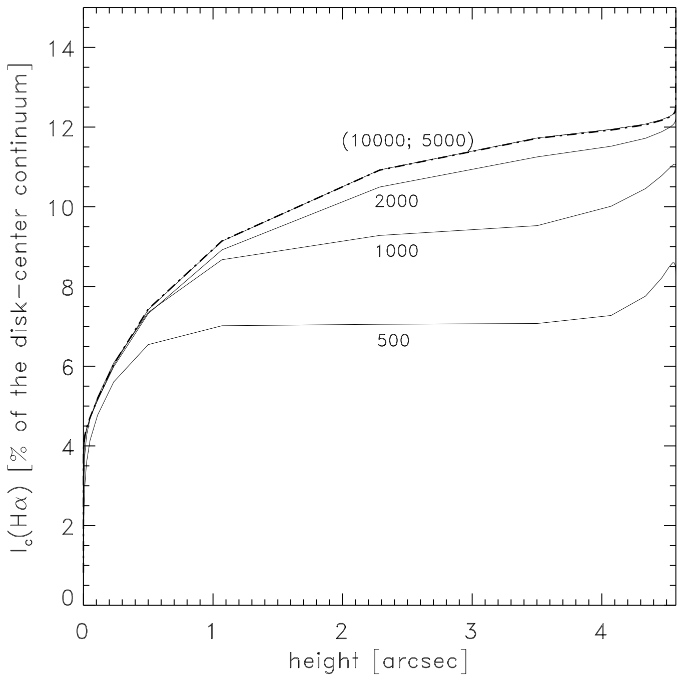

Fig. 3. Height variations of the Hα line center emergent intensity normal to the filament plotted against a geometrical scale in arcsec (≈ 700 km). The height reference is taken at the top of the slab. The greatest values obtained for D_y=10 000 and 5 000 km are almost identical at all heights. For decreasing slab widths, the emergent intensities decrease at all heights. None of these values exceeds 13% which is in contradiction with the argument that bright rims may be a natural part of filaments

We first notice in Fig. 3 that for geometrical widths greater than 5 000 km, emergent line center intensities saturate at all heights. This is demonstrated by an almost unique curve corresponding to the two widest slabs. Indeed, for the latter, the *horizontal* optical thickness becomes large enough ($\tau_y > 20$) for Hα line center intensity to be formed in these regions dominated by the incident radiation. Nevertheless, for these models Hα line profiles exhibit a central reversal whose $I_{\text{peak}}/I_{\text{center}}$ ratio increases with the slab width; this effect can be seen as well in Gouttebroze et al. (1993) results.

For narrower slabs (i.e. for decreasing widths), the emergent intensity decreases significantly at all heights. An explanation can be found in the reduction of the *lateral* optical thickness of Hα. This is in general agreement with the prominence results of Heinzel et al. (1994) showing how the Hα line integrated intensity correlates with the optical thickness at line center.

5. Discussion

It is obvious in Fig. 3 that *none* of the curves exceeds the critical value of 13% of the nearby disk-center continuum intensity.

This happens to be in strong contradiction with the possibility of formation of a bright rim within the filament. Although Hα line center intensities significantly greater than 13% can emerge from the *very* bottom regions of the slab, the extreme thinness of the relevant areas makes their observation practically impossible. We are aware that the latter statement is founded on the examination of a few models although it was possible to put in evidence significant 2D radiative transfer effects. A systematic two-dimensional radiative modelling of prominences and filaments, investigating relevant ranges of temperature, gas pressure and geometrical sizes is under progress and, based on these new results we shall be able to check out under which conditions bright rims may be visible.

Another point concerns the incident radiation adopted in the present study corresponding to the quiet sun emission. Indeed, as mentioned in Heinzel et al. (1995), an enhanced incident illumination due to the possible presence of an active region for instance, could improve the situation. Besides, other explanations on the nature of bright rims yet exist and cannot be ruled out. One of them will be investigated further such as the so-called "prominence blanketing" effect, i.e. a chromospheric brightening below the filament due to back-scattered radiation (Kostik & Orlova 1975). 2D models are well suited to such study which requires to examine the radiative interaction between the filament and the chromospheric regions underneath. It would be possible then, to determine quantitatively by which amount areas below the filament could be brightened up and then, evaluate this effect on the incident radiation back on the structure.

6. Conclusion

Two-dimensional radiative transfer effects on the Hα source function vertical variations in filaments were found significant. From our 2D computations we could not produce a bright rim being a part of the filament body. More generally, it shows to what extent the use of simple mono-dimensional slab models can be misleading for a further diagnostic of these structures. We finally believe that 2D radiative modelling of Hα, He I λ1083 nm and Ca II spectral lines for instance, can significantly improve the interpretation of present and future (THEMIS) ground-based spectroscopic observations. The same is true for strong UV lines which are actually observed from space with the SUMER and CDS instruments on-board SoHO.

Acknowledgements. This study was initiated at the Institute of Theoretical Astrophysics thanks to a post-doctoral fellowship supported by the University of Oslo, Norway. The *Société de Secours des Amis des Sciences* is greatly acknowledged for its financial support. Finally, I wish to thank Dr J. Aboudarham for his careful reading of the first draft of this article and the anonymous referee.

References

Auer L.H., Paletou F., 1994, A&A 285, 675
d'Azambuja L., d'Azambuja M., 1948, Ann. Obs. Paris-Meudon 6, 7
Gouttebroze P., Heinzel P., Vial J.-C., 1993, A&AS 99, 513
Heinzel P., Gouttebroze P., Vial J.-C., 1987, A&A 183, 351
Heinzel P., Gouttebroze P., Vial J.-C., 1994, A&A 292, 656
Heinzel P., Kotrč P., Mouradian Z., Buyukliev G.T., 1995, Solar Phys. 160, 19
Kostik R.I., Orlova T.V., 1975, Solar Phys. 45, 119
Paletou F., 1995, A&A 302, 587
Paletou F., 1996, A&A 311, 708
Paletou F., Vial J.-C., Auer L.H., 1993, A&A 274, 571

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.