

FORMATION OF THE Mg I $12\ \mu\text{m}$ LINES

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ABSTRACT The long-standing problem of the formation of the Mg I emission features near $12\ \mu\text{m}$ is solved by recognizing that the Mg I Rydberg levels maintain a departure diffusion flow to replenish NLTE population losses lower in the Mg I term diagram. We illustrate this Rydberg flow, its driving and its collisional control.

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INTRODUCTION

The riddle of the formation of the $12\ \mu\text{m}$ lines of Mg I has been solved by Chang *et al.* (1991) and Carlsson *et al.* (1991) in forthcoming papers to which we refer the reader for details. Figure 1 (taken from the latter paper) demonstrates that our computed center-to-limb profiles of the strongest $12\ \mu\text{m}$ line fit the observations very well; we also obtain excellent fits for weaker emission features and for Mg I Rydberg absorption lines in the infrared.

How do the emission peaks arise? As first suggested by Carlsson *et al.* (1990), they are a natural consequence of the replenishing of NLTE population depletion in a minority species from the population reservoir in the next higher ionization stage. The driving depletion is caused by photon losses in lines with large transition probability which become optically thin in the upper photosphere and by overionization from levels for which the bound-free edges are in the ultraviolet. The replenishment goes by step-wise departure diffusion along a ladder of close-lying Rydberg levels which is collisionally dominated at its top and which competes successfully with direct recombination into the depleted levels. We illustrate these properties here with further diagrams based on our detailed modeling in Carlsson *et al.* (1991).

SENSITIVITY TO RADIATIVE TRANSITIONS

The Grotrian diagram in Fig. 2 shows the levels in the triplet system included in the computations. Over 300 transitions are included in our model atom; this partial diagram shows only those to which the Rydberg departure flow is most

sensitive. The plot results from a “multi-MULTI” perturbation analysis in which 2525 converged NLTE solutions were obtained with MULTI while doubling all cross-sections (bound-bound, bound-free, radiative, collisional) one by one. The resulting height of the 12.32 μ m emission peak is used as sensitivity indicator; thicker lines are those of which doubling the oscillator strength results in larger emission. The 12.32 μ m line itself is present because larger strength increases its height of formation, so that the outward-rising NLTE line source function produced by the departure diffusion is sampled at larger height. Other emission-increasing lines such as $6h-5g$, $6g-4f$, $6f-3d$ and $6f-4p$ drive the Rydberg flow with their photon losses. The $4s-3p$ line is present because the $3p$ ionization edge is important in closing the flow back to the continuum.

Figure 3 shows computed emission changes against the optical depth in bound-bound transitions sampled at $\lg \tau_{500} = -3$ (where the line-center emission is formed). The plusses mark transitions with either $n \leq 6$ or $n \geq 7$ for both the lower and the upper level; these are the depopulation lines. They lie in the infrared and combine large transition probability with sufficiently small opacity to become optically thin in the upper photosphere, as evident here; lines with larger or smaller opacity have less effect. The asterisks mark lines which connect an upper level $n \geq 7$ with a lower level $n \leq 6$. These transitions provide alternative paths to the Rydberg flow through $n = 7 \rightarrow 6$. If they become stronger, more of the flow skips this ladder step so that the departure divergence between the levels is reduced. The lonely plus at $\lg \tau_{500} = 2.5$ marks the $4s-3p$ line.

SENSITIVITY TO COLLISIONAL TRANSITIONS

The collisional part of our “multi-MULTI” sensitivity matrix specifies the importance of collisions for the Rydberg flow. Increasing those collisional rates which form part of the Rydberg flow (the plusses in Fig. 3) produces *larger* non-LTE departure divergence, thus larger emission in the 12.32 μ m line. The increase is largest for the transitions $6g-5f$, $6h-5g$ and $8k-7i$ because enlarging their collision rates gains ladder-flow against direct recombination. The largest decrease is for $8s-7p$ because it provides a competing downward path, and for $7g-6f$, $7h-6g$ and $7i-6h$ itself because larger collision rates in these transitions maintain the same Rydberg flow for smaller departure divergence between the $n = 7$ and $n = 6$ manifolds.

NLTE THANKS TO COLLISIONAL COUPLING

Perhaps the most striking characteristic of the Rydberg departure flow is that it is dominated by collisions along the top of the Rydberg ladder: the 12 μ m NLTE emission peaks arise *because* the Rydberg collision cross-sections are large. A Rydberg departure flow exists only if sufficient recombinations enter at the top of the stepwise channel which the Rydberg levels provide from the continuum reservoir down to the photon-losing $n = 6$ and $n = 5$ levels, rather than go there directly; this is the case because the level-to-level coupling is sufficiently large to provide a wide channel. Rydberg atoms are geometrically large and the coupling is therefore primarily collisional. This is illustrated in Fig. 4 which displays the

dominance of collisions in the step-wise net rates between levels with $n > 5$. Thus, departures from LTE along the ladder arise because the collision rates along the ladder are high; in this case, collisional coupling maintains NLTE line formation!

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