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Partial Redistribution in the H Lyman Lines of Late-type Stars.

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Abstract. The effects of partial redistribution (PRD) in the formation of the hydrogen Lyman α and β lines are discussed with reference to simple atmospheric models of several late-type stars at different evolutionary stages. Radiative transfer calculations have been carried out using Carlsson's MULTI code which has been modified to include PRD by Hubeny & Lites. It is demonstrated that there is a rapid escalation in the importance of PRD in stars with surface gravity lower than the Sun, and that line profiles predicted using PRD are in significantly better agreement with observations than are those calculated assuming complete redistribution (CRD). The effects of PRD in H Lyman α on calculations of Fe II fluorescent spectra are examined, and it is found that there are significant, systematic differences between fluorescent spectra calculated using a PRD rather than CRD treatment of the pumping line.

1. Introduction

The modelling of the Lyman lines of hydrogen is extremely important for the study of stellar atmospheres. The Lyman α line is the strongest single emission line in the ultraviolet spectra of many cool stars and represents a significant energy loss mechanism from the high chromosphere and low transition region in most stars. The strength and width of the Lyman lines, particularly Lyman α and Lyman β, is such that they are important sources of fluorescence for lines of other elements (Jordan & Judge 1984).

The extremely high optical thickness of the Lyman lines together with the low electron densities in the region of line formation means that the treatment of photon scattering is very important in modelling these lines. The assumption of complete redistribution (CRD) during scattering is unacceptable for hydrogen because most scattering events in H Lyman α are coherent. This coherence significantly complicates the line profile calculation and the scattering must be modelled using partial redistribution (PRD).

Here I present the first detailed study of the effects of PRD in late-type stars with surface gravities (g) much lower than the Sun. PRD calculations have been performed with models of the stars listed in Table 1. These have been carried out using the MULTI code (Scharmer & Carlsson 1985) with the modifications made by Hubeny & Lites (1995) to include PRD effects, allowing for the depth and frequency dependent incoherence fraction that is required for a satisfactory treatment of the hydrogen lines. The α Tau model is from McMurry (1999); the other two models are new. This work is described in more detail by Sim (2001).

Table 1. Stars studied.

Star	HD	Spectral Type	$\log g$ ($\mathrm{cm\ s^{-2}}$)
α Tau	29139	K5 III	1.25
β Gem	62509	K0 III	2.75
Procyon	61421	F5 IV-V	4.00

2. Theory

The detailed theory of PRD in hydrogen is discussed by Cooper, Ballagh & Hubeny (1989). The physical quantity at the heart of PRD is the incoherence fraction, Λ, which is the fraction of photon scattering events which are (in the rest frame of the scattering atom) incoherent. Incoherence occurs because of elastic collisions between the scattering atom and electrons or ions in the plasma. PRD effects are largest when the incoherence fraction is small and since elastic collision rates decrease with decreasing density, the difference between CRD and PRD will be greatest in low gravity stars.

3. Line Profiles

Fig. 1 shows the calculated Lyman α and β line profiles using two different redistribution cases:

(i) CRD throughout;
(ii) PRD in both Lyman α and β.

The primary difference between the PRD and CRD profiles is a significant reduction of the strength of the Lyman α wings, which occurs because with PRD fewer photons are redistributed from the line core to the wings. The differences between PRD and CRD are smaller in the Lyman β profile because the Balmer α decay route makes coherent Rayleigh scattering relatively less important. However, it is clear from Fig. 1 that PRD effects in Lyman β are still noticeable in the giant stars. The treatment of Lyman β has little effect on the calculated Lyman α profile, but the calculated Lyman β profile is sensitive to the treatment of both lines. There is an increasing difference between the PRD and CRD profiles with decreasing gravity: the integrated Lyman α flux is smaller in PRD than CRD by factors of 2.4 in Procyon, 3.5 in β Gem and 4.7 in α Tau.

Fig. 2 shows calculated Lyman α profiles, corrected for interstellar absorption as described by Sim (2001), and profiles observed with *IUE* (α Tau) and *GHRS* (β Gem and Procyon). Although there are clearly differences between the calculated and observed profiles (owing to deficiencies in the current atmo-

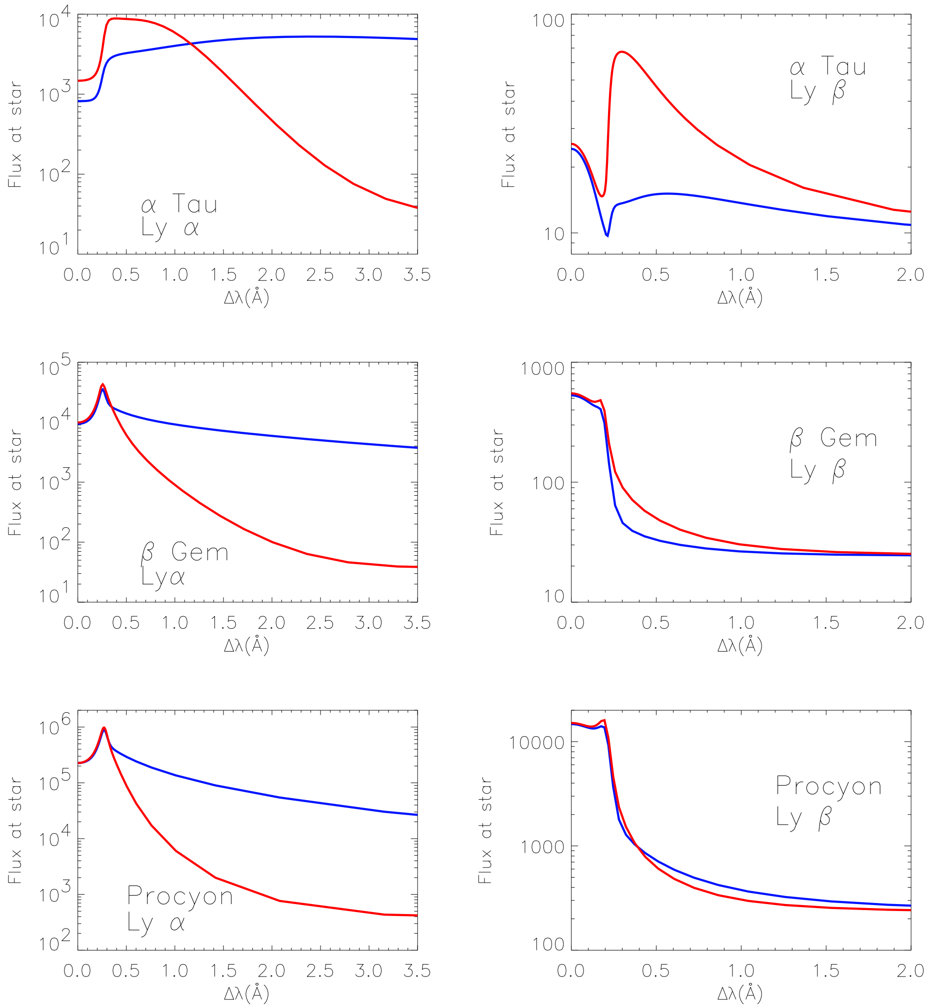

Figure 1. Calculated H Lyman α (left panels) and H Lyman β (right panels) profiles for each of the three stellar models. CRD in blue, PRD in red. Fluxes are in ergs cm^{-2} s^{-1} $\mathrm{\AA}^{-1}$ and $\Delta\lambda$ is wavelength interval from line centre.

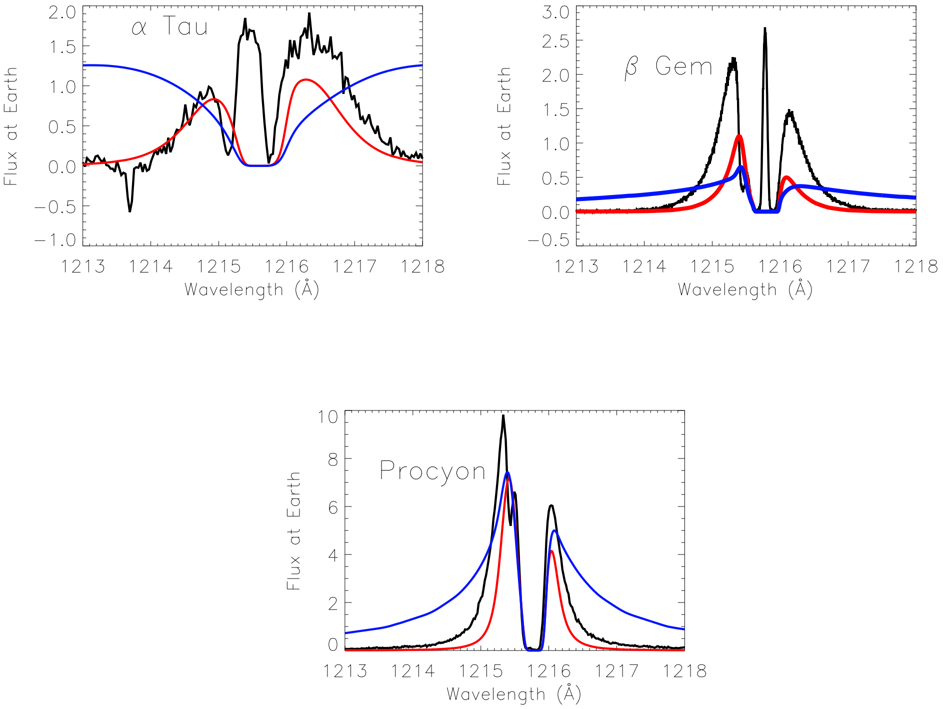

Figure 2. Calculated and observed H Lyman α profiles. Observed profile is black, PRD calculation is red and CRD calculation is blue. Fluxes are in 10^{-11} ergs cm^{-2} s^{-1} Å^{-1}. The sharp peaks near the line centre in α Tau and β Gem are due to geocoronal emission.

spheric models), it is clear that the shapes of the PRD profiles are in better agreement with the observations than are the CRD profiles.

4. Fluorescence

Low gravity stars such as α Tau show rich fluorescent spectra including lines of Fe II, H_2 and O I which are pumped by Lyman α and Lyman β; the interpretation of these spectra requires reliable modelling of the Lyman lines. To illustrate the importance of PRD, synthetic Fe II fluorescent spectra (as pumped by Lyman α) have been calculated using the α Tau model and atomic data from Kurucz & Bell (1995), in a similar fashion to McMurry, Jordan & Carpenter (1999). Fig. 3 shows two regions of the synthetic spectrum calculated using both CRD and PRD treatments of Lyman α. The calculations assume that the Fe II lines are optically thin, so ratios of lines from a common upper level may not be accurate. It is also assumed that the lower level populations follow the Boltzmann distribution (as justified by McMurry et. al. 1999). The results show that there are significant differences in the fluxes calculated using PRD rather than CRD in the pumping Lyman α line.

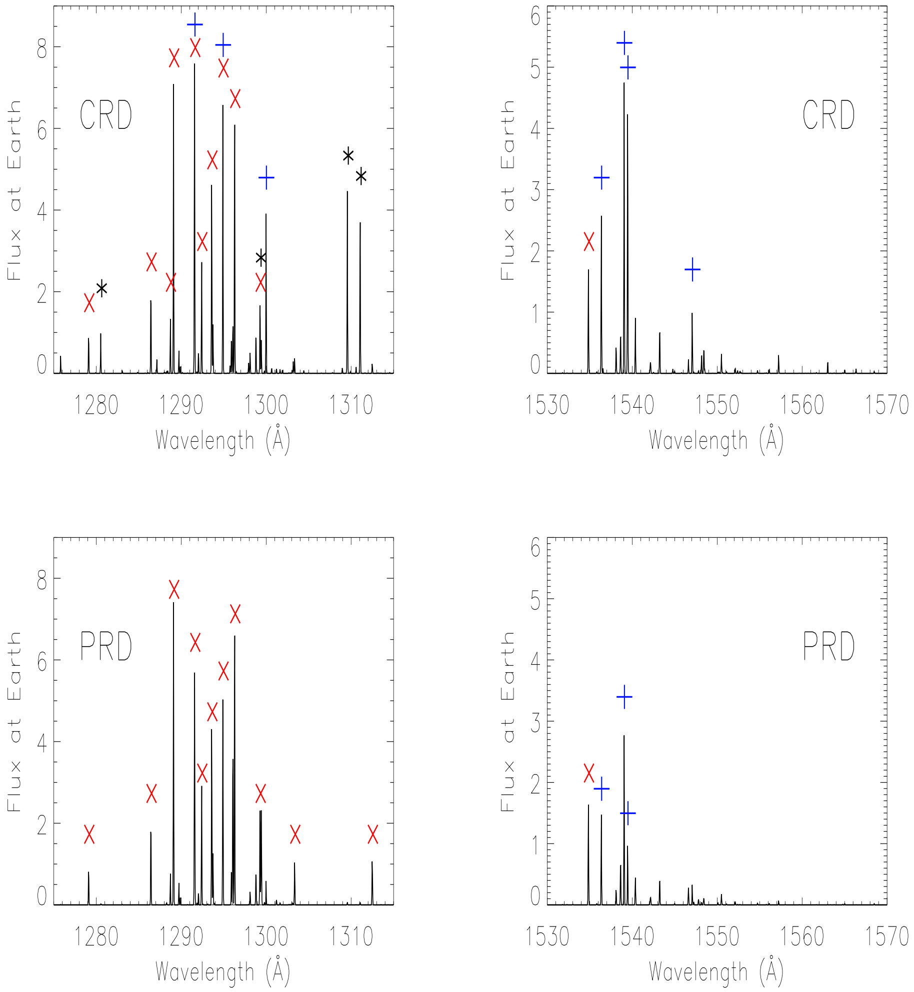

Figure 3. Synthetic spectra of Fe II fluorescent lines in α Tau pumped by H Lyman α. Lines marked with a red $\times$ are pumped within 2 Å of line centre, those with a blue $+$ are pumped between 2 and 4 Å from line centre and those with a black $*$ are pumped beyond 4 Å from line centre. Upper panels use CRD Lyman α and lower panels use PRD Lyman α. Fluxes are in 10^{-13}ergs cm^{-2} s^{-1} Å^{-1}.

Observations of Fe II fluorescent lines are discussed by McMurry et. al. (1999). Several lines which are pumped in the Lyman α wings appear in the synthetic CRD spectrum but are absent from the PRD and observed spectra. Also, the ratio of the two lines near 1539 Å is closer to that observed when using PRD. When comparing observed Fe II fluxes in α Tau with those calculated from the model, McMurry et al. (1999) found a systematic trend that lines pumped in the blue wing of Lyman α were underpredicted by about 13% while those pumped close to line centre in the red wing were underpredicted by a factor of 3.7; the authors suggested that this may be due to their CRD treatment of Lyman α. Comparing the PRD-based fluorescent fluxes with the observed fluxes given by McMurry et al. (1999), I find that the lines pumped in the blue wing are underpredicted by a factor of 2.3 while those near line centre are underpredicted by a factor of 2.2, indicating that PRD eliminates the wavelength dependence found by McMurry et al. (1999). This provides powerful evidence that the PRD approach to the modelling of the Lyman α line is more realistic than using CRD.

5. Conclusions

PRD effects are very important in modelling the H Lyman lines in all late-type stars, and increase significantly as the surface gravity decreases. The direct effect on the line profile is largest in the Lyman α line wings, but is also important in Lyman β.

When calculating the Fe II fluorescent spectrum, the differences between the H Lyman α PRD and CRD profiles lead to detectable changes in the relative Fe II line intensities. In particular, fluorescent lines which are pumped in the line wings are predicted to be weaker when a PRD calculation is used for the pumping line.

Additional results concerned with the effects of PRD on the ionization balance of hydrogen and the usefulness of various approximate PRD methods are discussed by Sim (2001).

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