DIELECTRONIC RECOMBINATION AND THE SOLAR H AND K LINES

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ABSTRACT

Quantitative investigations of the role of dielectronic recombination in the H and K lines have been carried out by numerically solving for the K line source function for a two-level atom with complete redistribution. It is found that:

a) The direct contribution of the new process to the emission reversal must be considerably less important than originally suggested, because the large electron density required to support the process causes the line source function to rise to the Planckian in the region of formation of the emission reversal, thus dominating over the dielectronic emission.

b) The indirect contribution of the process to the emission, via locally increasing the effective ε in the transfer equation and thus locally raising the K line source function, cannot be effective if there is complete redistribution in the line.
I wish to report on recent investigations on the possible role of dielectronic recombination in the formation of the Ca$^+$ H and K lines. The process, as originally suggested by Goldberg (1964), involves transitions between doubly excited 4pn$l$ states and singly excited 4sn$l$ states of the neutral calcium atom. For high $n$, these transitions have very nearly the same wavelength as the resonance transition 4p - 4s of the calcium ion (H and K lines). The 4pn$l$ states of calcium lie above the 4sn$l$ series limit, and thus are subject to auto-ionization, provided $l$ is not too large. Those states that are subject to auto-ionization are populated according to LTE relative to the free electrons, and also give rise to very broad emission lines because of the short lifetime for auto-ionization of the upper state. If we assume that the population of the lower (4sn$l$) levels of these transitions is negligible, then the source function in the neighborhood of the K line may be written as the sum of the ordinary source function and a term due to 4pn$l$ - 4sn$l$ transitions:

$$ S_\nu = B(T_{ex}) + r_\nu B(T_e), $$

where $T_{ex}$ is the excitation temperature for the K line, $T_e$ the electron temperature, $r_\nu = p(\tau) j_D(\nu) / \phi_K(\nu)$, and

$$ p(\tau) = 10^{-16} n_e T_e^{-3/2} G. $$

$G$ is the total statistical weight of the 4pn$l$ levels taking part in the process. $j_D$ is the normalized mean emission profile for the 4pn$l$-4sn$l$ transitions; we may assume, for instance, that the mean profile is Lorentzian with a damping constant equal to $A_a / 4\pi$, where $A_a$ is the mean auto-ionization rate. $\phi_K$ is the normalized absorption profile for the K line.

The original suggestion (Goldberg, 1964) that dielectronic recombination might be a major contributor to the H and K line cores stemmed from the observation that if we assume $n_e = 10^{12}$, $T_e = 6000^\circ$, $T_{ex}(K) = 3800^\circ$, $G = 3 \times 10^4$, and $j_D / \phi_K = 3 \times 10^3$, then...
\[ \frac{r_v B(T_e)}{B(T_{ex})} \approx 0.7. \] (The values of \( n_e \) and \( T_e \) are from Pagel's model (1961) for \( h = 300 \) km. \( T_{ex} \) is that temperature appropriate to the observed intensity of \( K_3 \), and \( J_D/\phi_K \) is that profile ratio expected at the wavelength of the emission reversal if \( A_\alpha \approx 3 \times 10^{11} \text{sec}^{-1} \). \( G \) is the total statistical weight obtained from all \( 4p \) levels up to \( n = 30 \).) This ratio is about the size of the observed ratio

\[ \frac{[I(K_2) - I(K_3)]}{I(K_3)} \] in the quiet sun, which suggests that under the above conditions dielectronic recombination could supply by itself enough intensity to produce the emission peaks.

An additional mechanism suggested was that the term \( r_v B(T_e) \) might locally raise the line source function \( B(T_{ex}) \) itself. Solution of the transfer equation showed this to be the case with the assumption of coherent scattering in the wings. Indeed, it was possible with this assumption to reproduce reasonably well the magnitude, position, and center-to-limb variations of the emission cores from the numerical values given above (Goldberg and Noyes, 1964). We had not at that time, however, investigated quantitatively the effect on the line source function using the more realistic assumption of complete redistribution.

Dr. Avrett and I have recently examined both these mechanisms in more detail by actually solving numerically for \( B(T_{ex}) \), given \( T_e(\tau) \) and \( n_e(\tau) \), and assuming a two-level atom, complete redistribution, and a Voigt profile for the K line. We find that the ratio \( r_v B(T_e)/B(T_{ex}) \) cannot be nearly as large as originally suggested, for reasons which may be summarized qualitatively as follows: A large value of \( r_v \) requires a large value of \( n_e \), which in turn implies a large value for \( \epsilon \), the ratio of collisional to radiative de-excitation in the K line. For \( n_e = 10^{12} \) and \( T_e = 6000^\circ \), for instance, \( \epsilon \approx 3 \times 10^{-3} \) (Van Regemorter, 1962). This causes \( T_{ex} \) to approach \( T_e \) at a rather moderate line-center optical depth, say \( \tau_0 \approx 10^3 \). However, the emission originates in a region where
\( \tau_0 > 10^4 \). Thus in the region of interest \( T_{\text{ex}} \sim T_e \), and \( r_\nu B(T_e) / B(T_{\text{ex}}) \sim r_\nu \leq 0.02 \).

Detailed calculations of the K line source function with Pagel's model have shown:

(a) The effect of dielectronic recombination on the line profile is indeed to raise the \( K_2 \) peaks by about one per cent (using \( G = 3 \times 10^4 \) and \( A_a \sim 3 \times 10^{11} \text{sec}^{-1} \)).

(b) The \( K_2 \) intensity is much too high, i.e., \( I(K_2) \sim B(T_{\text{ex}}(\tau_0 = 10^4)) \sim B(T_e(\tau_0 = 10^4)) \sim B(6000^\circ) \), whereas the observed \( I(K_2) \sim B(4200^\circ) \) (Goldberg, Mohler, Mueller, 1959). We must conclude then that either \( \epsilon \) (and therefore \( n_e \)) or \( T_e \) is much lower at \( \tau_0 = 10^4 \) than indicated in the model used.

Our investigation of the effect of the 4pnl-4snf transitions on the line source function showed it to be completely negligible in the case of noncoherent scattering, as opposed to the results for coherent scattering. For coherent scattering, the parameter \( \epsilon \) in the transfer equation becomes \( \epsilon + r_\nu \), and in the wings \( r_\nu \gg \epsilon \). But for noncoherent scattering, \( \epsilon \) becomes \( \epsilon + \int_0^\infty r_\nu \phi_\nu d\nu = \epsilon + p \), and in general \( p < \epsilon \). Indeed, the ratio \( p/\epsilon \) is essentially the ratio of the rates of dielectronic recombination to radiative de-excitation in the K line.

Thus we conclude that: (a) the direct contribution to the K line by dielectronic recombination cannot increase the emission by more than a few per cent, and (b) the influence of the process on the line source function is negligible, unless there is partial coherency in the wings.
References

DISCUSSION

Burgess: The G which should be used here cannot be quite as large as the one you have quoted.

Noyes: The value quoted is consistent with that obtained from the relation for the dielectronic recombination rate which you presented at the Liège Symposium.

Burgess: In that expression the sum over n is taken to infinity, which is valid only for the zero density case. In the paper that I gave earlier at this meeting I show that this quantity is very much reduced for densities appropriate to the solar chromosphere. I think the only situation in which the dielectronic process might give an appreciable contribution to the line radiation is when the temperature is so low that the line can only just be excited. One might then perhaps exploit the Boltzmann factor \( \exp(-E/kT) \), since the effective value of E in the dielectronic process is a little smaller than in collisional excitation. The line would then of course have to be a weak line.