NON-LTE MODELS OF SOLAR PROMINENCES

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ABSTRACT. We briefly review some representative non-LTE models of solar prominences, developed during the past decade. Particular attention is devoted to recent interpretation of hydrogen Lyman α line profiles in quiescent prominences and to the solution of the non-LTE problem for moving active prominences. Finally, we outline some of the most important prospects of prominence plasma diagnostics.

НЕ-ЛТР МОДЕЛИ СОЛНЕЧНЫХ ПРОТУБЕРАНЦЕВ. В настоящей работе предлагается короткий обзор некоторых представительных не-ЛТР моделей солнечных протуберанцев которые были разработаны в течении последних десяти лет. Особое внимание посвящено интерпретации профилей водородной линии Лайман-α в спокойных протуберанцах и решению задачи не-ЛТР для движущихся активных протуберанцев. В заключении перечислено несколько наиболее важных направлений дальнейшего развития диагностики плазмы протуберанцев.

NON-LTE MODELY SLUNEČNÍCH PROTUBERANCÍ. V práci je podán stručný přehled některých representativních non-LTE modelů slunečních protuberancí, vyvinutých během posledních deseti let. Zvláštní pozornost je přitom věnována interpretaci profilů vodíkové čáry Lyman α v klidných protuberancích a řešení non-LTE problémů pro pohybující se aktivní protuberance. V závěru je

naznačeno několik nejdůležitějších směrů dalšího rozvoje diagnostiky protuberanční plazmy.

1. INTRODUCTION

In the past decade, a significant effort was devoted to prominence non-LTE modelling, both from a purely theoretical point of view and by using new space and ground-based observations. However, nearly all models published so far can be regarded as "first-order approximations" which do not account properly for the complicated geometrical structure of solar prominences. We would rather deal with the class of "mean" models, as in most chromospheric studies. There are two reasons for this: neither diagnostically important UV-observations from space, nor some of the ground-based measurements provide sufficient spatial resolution and, moreover, the theoretical multidimensional solutions require large computational facilities which are only now becoming available. In addition, most attention has been devoted to non-LTE studies of quiescent prominences which are assumed to be in a stationary state without any considerable macroscopic motions. In the present contribution, we briefly review the most important non-LTE computations, which have been carried out during the last decade, and then concentrate on some results recently obtained in non-LTE synthesis of the prominence hydrogen spectrum, both in quiescent and active (moving) objects.

2. NON-LTE MODELS

In a series of papers, Heasley et al. (1974, 1976a,b) use the technique of complete linearization to model quiescent prominences, approximated by one-dimensional (1D) vertically positioned slabs of finite thickness. The observable quantities, derived from these models, are the integrated intensities of hydrogen and helium lines. The atomic models used are complex, including many bound as well as continuum levels for which the excitation and ionization equilibria are treated simultaneously with the radiative transfer in several lines and continua. However, although these models seem to be the most sophisticated so far published (from the point of view of inherent non-LTE physics), they have several serious drawbacks: their geometry is too simple, complete frequency redistribution (CRD) in resonance Lyman lines, only schematic incident radiation fields have been used for some lines which strongly affects the emergent line intensities, the energy balance is treated either via the radiative equilibrium (leading to too low temperatures inside the slab), or isothermal-isobaric models have been adopted. In a subsequent paper, Heasley and Milkey (1978) performed more refined calculations also including other atomic species for diagnostics, which led to a new set of low-pressure isothermal and isobaric models. These models seem to agree in general with the optical observations of Landman and Illing (1977), but neither the Lyman lines, nor the Lyman continuum have been synthesized from such models. Only recently, Heasley and Milkey (1983) tried to compare the Lyman continuum observed by Skylab with the synthetic continuum based on these low-pressure models. Other authors used much less complex approaches to evaluate the prominence spectra, devoting great attention to subordinate (Balmer) lines of hydrogen (see, e.g., Yakovkin et al., 1979, or Tsovookhuu, 1980, or Morozhenko, 1984). However, there exists a category of simpler non-LTE models (two or three hydrogen levels, CRD, isothermal-isobaric structure) which try to account - at least in a schematic way - for the effects of multidimensional radiative transfer. Vial

(1982) has performed some two-dimensional (2D) computations for L α, CaII and MgII lines, using the code of Mihalas et al. (1978), a two-level model atom and CRD. Although these models give line profiles comparable to those obtained from the OSO-8/LPSP UV-spectrometer, they correspond to one 2D structure, while we typically observe complicated filamentary structures which can be responsible for important effects of lateral radiation transport. The problem of radiative transfer in inhomogeneous prominences was partly treated by Morozhenko (1978), Zharkova (1983), or Fontenla and Rovira (1985). The emergent hydrogen-line profiles have been found to be different when compared to one-slab models, but these 1D multilayer representations still do not account for the free penetration of the incident and diffusive radiation.

All the abovementioned papers deal with more or less sophisticated non-LTE modelling of quiescent prominences, and try to develop satisfactory diagnostics. On the other hand, no similar computations exist for active objects, presumably due to the presence of macroscopic velocities, which further complicates the solution of the transfer problem, and also due to the lack of suitable observations which would stimulate such research. To fill this gap, from a theoretical point of view, we have performed several non-LTE computations for the hydrogen prominence plasma moving in the corona; the results are discussed in Section 4. Returning to the quiescents, all important non-LTE studies, briefly mentioned herein (for a more comprehensive discussion, refer to Hirayama's review, 1985) are based on the assumption of CRD in all lines. Since the prominences are generally low-density objects, we expect certain departures from CRD, at least in strong resonance lines like the Lyman hydrogen lines. With the good line profiles from the OSO-8/LPSP or SMM/UVSP instruments, we are now ready to assess the importance of such departures. This particular problem is discussed in the following section.

3. PARTIAL REDISTRIBUTION IN HYDROGEN LYMAN-α

In a recent paper by Heinzel et al. (1986) (hereafter referred to as HGV), the problem of the formation of the hydrogen Lyman α line in quiescent prominences was thoroughly investigated by using the most up-to-date theoretical results for PRD in this line, on the one hand, and the observed line profiles from the OSO-8/LPSP spectrometer, on the other. This exploratory work was aimed at establishing the actual importance of the PRD effects in the formation of hydrogen resonance lines and, therefore, HGV used isothermal-isobaric slab models similar to those discussed previously (this selection avoids other competitive effects which could, in principle, arise from a more realistic geometry, velocity fields, or a depth-dependent structure of the physical variables). However, contrary to most previous studies, HGV devoted great attention to as precise a specification as possible of the radiation fields incident at the prominence surface boundary. The observed specific intensities of the photospheric and chromospheric radiation fields have been used to determine the mean incident radiation fields in all lines and for all continua at a given height above the solar surface. The coupled non-LTE problem of radiative transfer and statistical equilibrium (for a five-level hydrogen atom with continuum) was then solved numerically by a linearization method similar to that of Mihalas et al. (1975). In order to account explicitly for PRD in Lyman α and also in Lyman β, HGV applied, to an advantage, the modified equivalent-two-level-atom approach of Hubený (1985). PRD in Lyman α was treated according to Yelnik et al. (1981), which represents the most complete theoretical attempt to describe partially coherent scattering in this line. By varying the basic input parameters (total column mass M, kinetic temperature T, total gas pressure p, and turbulent velocity v_t), HGV obtained a set of theoretical line profiles which were subsequently compared with the available data. It was demonstrated that the PRD Lyman α line profiles reproduce the prominence profiles observed on board of OSO-8 quite well. On the other hand, the CRD profiles are in no case capable of explaining these observations. The most important feature of the PRD Lyman α profiles is that they exhibit two well-pronounced peaks, located at wavelengths roughly corresponding to those of the chromospheric Lyman α peaks. This behaviour is actually observed; see Fig. 3 in HGV. Note that qualiatively the same observations also come from the SMM/UVSP instrument (A. Poland - private communication). The double-peaked behaviour of the prominence Lyman α profiles is a consequence of quasi-coherent diffusion of the incident solar radiation through the prominance slab. In fact, original chromospheric peaks are partly reproduced by quasi-coherent diffusion of near-wing photons, while in the CRD case these photons are spread over the absorption profile.

The integrated intensities of Lyman α and H α are also in reasonable agreement with the observations reported by Heinzel and Vial (1983). However, the simple isobaric and isothermal slab models with "standard" PRD (for the definition see Hubený, 1985) give much lower integrated intensities of the Lyman β line than the OSO-8 measurements. This discrepancy, found by HGV, seems to be of a similar nature to that of chromospheric Lyman β. This Lyman β problem requires further investigation in order to specify the conditions responsible for this discrepancy.

To summarize, HGV have made the first direct comparison between PRD and observed Lyman α profiles, and have concluded that PRD is a quite satisfactory approximation in this situation.

4. HYDROGEN EMISSION FROM MOVING PROMINENCES

Heinzel and Rompolt (1986) (hereafter referred to as HR) have made the first more detailed non-LTE computations taking into account the macroscopic motions of prominences in the corona. They used simple 1D geometry with uniform temperature and pressure, and the same numerical code as in HGV (CRD is assumed for the first approximation). The motion is then simulated by prescribing the corresponding velocity-dependent boundary conditions. The radially moving prominence exhibits important brightness variations which depend on the velocity, prominence height, and plasma parameters M, T, p, v_t (see preceding section). These variations can be explained in terms of the Doppler brightening and/or Doppler dimming effects (DBE, DDE) - see Hyder and Lites (1970). Irrespective of height, we can summarize the following conclusions: For lower electron densities n_e, the line source function is radiatively dominated and, therefore, DBE and/or DDE are most pronounced. If $n_e \simeq 10^{10}$ cm^{-3}, the prominence H α brightness (i.e. the integrated line intensity) can be three or more times greater than that corresponding to the static case (for velocities around 160 km s^{-1}), while L α exhibits typical DDE for all velocities. On the other hand, L β brightness increases in the same way as the H α for radial velocities up to about 80 km s^{-1}, and then rapidly decreases due to DDE in L β itself. At higher electron densities, the line source function becomes collisionally dominated and thus much less sensitive to prominence motions. If $n_e \simeq 10^{13}$ cm^{-3}, we observe practically no DBE or DDE in hydrogen lines. An increase of T and/or v_t generally leads to enhanced line emission, but this effect is diminished when the velocity increases. The H β line behaves like the H α, and other Balmer lines exhibit less pronounced DBE. Note that the two-level approximation used by Rompolt (1980a,b) overestimates the importance of DBE in Balmer lines.

5. CONCLUSIONS

We have reviewed some of the attempts to solve the non-LTE radiative transfer problem in solar prominences. Each of these approaches concentrated on one or two particular aspects, i.e. multilevel interlocking (Heasley et al.; Yakovkin et al., 1979; HGV), multidimensional effects (Vial, 1982; Zharkova, 1983; Fontenla and Rovira, 1985), PRD (HGV), energy balance (Heasley et al.; Fontenla and Rovira, 1985), prominence motions (HR), but none of these studies treated all these important aspects more comprehensively. The most important problems to be solved in the future seem to be the following: the problem of global energy balance (estimates of cooling rates), multidimensional-multilevel transfer through the prominence filamentary structure (the effect of $H\alpha$-line polarization, the explanation of $L\beta$ emissivity), diagnostics of the temperature structure of the prominence-corona transition region and of the interfillar medium (see also Heinzel et al., this volume), PRD-interlocking, inclusion of more realistic MHD equilibria. Further development of radiative hydrodynamics for moving objects is also highly desirable. As regards observations, we need simultaneous observations in as many lines as possible, as well as in some UV continua made with high spatial (filamentary structure), spectral (coherent scattering, motions, etc.) and time (rapidly developing objects) resolution.

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