HYDROGEN LINE PROFILES

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1. Introduction

Observed hydrogen line profiles are an enormously important source of diagnostic information about virtually all kinds of astronomical bodies. Therefore, it is important to understand the hydrogen line formation in sufficient detail to be able to achieve a high degree of reliability by analyzing observed hydrogen line profiles.

Calculation of the predicted hydrogen line profiles involves two basic ingredients, (i) intrinsic line profiles, or line broadening – "atomic physics" part, and (ii) the radiative transfer problem – "astrophysics" part. There is not enough space to discuss here the current status of the astrophysical part of the problem. Fortunately, this topic is covered by many reviews. There are two major problems here, (a) departures from local thermodynamic equilibrium (LTE) – the so-called non-LTE description (e.g. Mihalas 1978; Hubeny *et al.* 1994); and (b) departures from complete frequency redistribution (Cooper *et al.* 1989; Hubeny and Lites 1994).

2. Basic Physics of Line Broadening

Line broadening is either due to the spontaneous radiative decay of excited levels – *natural* broadening, or due to an interaction of the radiating atom with the surrounding particles – *pressure* broadening. If the perturbing particles are charged (electrons and protons) one refers to the *Stark* broadening, while the broadening by hydrogen atoms is termed *resonance* broadening. Finally, the presence of an external magnetic field leads to the *Zeeman* broadening (e.g. Mathis 1984).

Traditionally, the calculations of the hydrogen Stark broadening were based on two usual approximations: the impact and the quasi-static limits. The impact limit is based on two assumptions: the duration of collision is

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much shorter that the interval between collisions, so that the collision are separated in time, and the time of interest is much larger than the duration of collision. (The time of interest, or evolution time of the atomic dipole, is essentially the inverse of the detuning from the line center). On the other hand, the quasi-static limit is suitable as soon as the time of interest becomes so short that the perturbers may be viewed as static during the emission or absorption of radiation.

Hydrogen line broadening was originally treated assuming the impact approximation for electrons, and quasi-static approximation for ions (Griem *et al.* 1959; Griem 1974). Some discrepancies with experimental results required various improvements. In particular, it was shown that the so-called Unified Theory (Smith *et al.*, 1969; Voslamber 1969) gives a satisfactory results for electron broadening. Vidal *et al.* (1973) have published an extensive grid of line profiles for the first four members of the Lyman and Balmer series. This grid was then widely used in astrophysical applications.

There are several domains where this well-established theory breaks down: (i) for low densities – because radiative processes during a collision can be important, and also the static limit for ions is not reached; (ii) for high densities – because strong collisions may overlap; and/or (iii) for very far wings – because of very short dipole evolution time. The first effect was studied by Cooper et al (1974), and by the Meudon group (Stehlé *et al.* 1983; Stehlé and Feautrier 1984, 1985). The latter authors used the Model Microfield Method (MMM - Brissaud and Frisch 1971) to study the ion dynamic effects, and showed that for Hα the ion broadening is well described by the impact approximation in the line core. They also showed that the effect of spontaneous emission during collision may in principle be important for low densities, but in most astrophysical applications these effect are completely masked by the Doppler broadening.

Finally, in the very far line wings, particularly for Lα, the interaction occurs at a very short distance between the radiating atom and a hydrogen atom or a proton, eventually leading to the formation of well-known molecular H_2 and H_2^+ satellites (Allard and Kielkopf 1991; Allard and Koester 1992).

3. Level Dissolution and the Line Merging near the Series Limits

Interactions of the radiating atom with surrounding particles is responsible not only for line broadening, but also for a perturbation of high-lying atomic levels which are becoming progressively broadened and finally dissolved. This has a profound influence on the shape of monochromatic opacity on the immediate longward side of a continuum threshold.

The dissolution of high-lying atomic levels by plasma perturbations has

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been treated by a number of authors in terms of *occupation probabilities*, which for LTE plasmas can be defined as the ratio of the level populations to those in the absence of perturbations. A phenomenological theory for these quantities has been given by Hummer and Mihalas (1988), who also discuss at length earlier work in this area. Expression for the absorption coefficient of the plasma in terms of occupation probabilities have been given by Däppen *et al.* (1987). Seaton (1990) has extended these results by developing a line broadening theory that goes smoothly into line dissolution as the strength of the perturbation increases. Similar, but independent calculations of the hydrogen opacity near the series limits including the effects of level dissolution have been presented by Stehlé and Jacquemot (1993). Finally, Hubeny *et al.* (1994) have extended the Däppen *et al.* formalism to non-LTE situations. They have also presented useful formulae for the occupation probabilities and for the line profiles of high series members.

4. Conclusions

The theory of hydrogen line broadening is well developed. It provides a sufficiently accurate description for most astrophysical applications. Likewise, the theory of line merging near the series limits is now put on a firm basis. Finally, the theory of frequency redistribution in hydrogen lines is well established. Astrophysicists thus have sufficient tools to predict accurate hydrogen line profiles to be used for quantitative spectroscopic diagnostics.

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DRAVINS TO R. CAYREL Q. In the line spectrum of the Sun, and especially for strong line profiles, it is dangerous to use an extended source as the Moon for comparison with point source star. Scattering may be present in an imperfect spectrograph.
A. Partaking the worry you are telling us, for at least a couple of years we have been taken as integrated solar spectrum the spectrum of Vesta or Ceres. But we also took the solar spectrum scattered by the Moon, and because we were unable to found any difference in the observations coming from these two sources we eventually stopped taking spectra coming from the asteroids for saving telescope times.

J. MATTHEWS to A. GOMEZ Q. I notice in your table of open cluster distance moduli that there are two clusters (IC2391 and NGC 2632) which have comparable π and numbers of stars observed N but uncertainties which differ by a factor of >2. Why ?
A.The main reason is that these clusters have different ecliptic latitudes (β). β values are about +2 degres for Praesepe stars (NGC 2632) and about -66 degres for IC 2391 stars. In fact, the standard error on parallax for a star depends on the H-magnitude and the ecliptic latitude of the star. Stars near the ecliptic were less well observed than those near the poles. This effect alone can account for a degradation by a factor 2 of the standard error.

B. WEAVER to A. GOMEZ Q. Do you have any figures of lower main sequence or pre main sequence stars?
A. No, I haven't. These results are preliminary and can be analysed only from a statistical point of view.

(continued after the paper by Mathys)

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