The Universe at Low Radio Frequencies
IAU Symposium, Vol. 199, 2002
A. Pramesh Rao, G. Swarup and Gopal-Krishna, eds.

Populations of Hydrogen-like Atoms or Ions and Radio Recombination Lines (RRL's) Interpretation.

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Abstract. The problem of non-LTE populations has been considered in terms of the departure coefficients $\frac{\partial b_n}{\partial n}$ as functions of the kinetic temperature T_e, the electron density N_e, the continuum radiation flow $I_c$and the ratios of $I_{Hn\alpha}, I_{Hn\beta}, I_{Hn\delta}$ and $I_{Hn\varepsilon}$ (the line radiation flows). The ratio of $I_{Hn\alpha}/I_{Hn\beta}$ are sensitive to the thermal radiation from HII regions. Characterized by the relation of $\frac{\partial^2 b_n}{\partial n^2} > 0$, the populations are shown to be inhabited radiatively.

1. Introduction

The numerical programmes by Brocklehurst & Salem (1979) provide an exact solution to the balance equations for hydrogen-like, highly excited atoms in the model, constructed by Seaton (1964) and supplemented with the details by Dyson (1967), Shaver(1975) and Hoang-Binh (1986). RRLs are observed in the centimetre and millimetre wave bands (Cersosimo & Magnani,1990; Gordon & Walmsley,1990; Anantharamaiah et al 1988; Hoang-Binh et al 1985). The analytical methods have been stimulated by experiments at the low-frequency range. The low-frequency lines are formed between the levels with numbers $n = 308 - 750$ and they are observed by Sorochenko et al (1984), Konovalenko (1984) and Anantharamaiah et al (1992) with the instruments of UTR-2 (Kharkov), DKR-1000 (Pushino) and NRAO. The balance equations are analytically solved for the superhigh levels of $n = 600 - 1000$ by Vainstein et al (1979), Beigman (1987) and Rovenskaya (1992). Owing to the interaction of hydrogen-like atoms and ions with this thermal radiation of the radio sources with flat Rayleigh-Jeans spectrum, the ratio of RRL flows can be estimated as follows $I_{Hn\alpha}/I_{Hn\beta} \sim (n\beta/n\alpha)^{3.3}$ and $\frac{\partial^2 b_{n\beta}}{\partial n\beta^2} > 0$, where $n\alpha, n\beta$ are the numbers of RRLs. Owing to atomic collisions with electrons the analogous magnitude takes the form $I_{Hn\delta}/I_{Hn\varepsilon} \sim (n\varepsilon/n\delta)^3, \frac{\partial^2 b_{n\delta}}{\partial n\delta^2} < 0$ and $n\delta < n\varepsilon$. The well-known numerical programmes by Brocklehurst & Salem (1979) are complemented with the $\frac{\partial b_n}{\partial n}$-factors for heavy ions of He,C and Fe.

The temperature and the density of HII region are calculated as functions of the kinetic coefficients.

$$D^c n^7 > D^R n^{7.3}, D^{BB} n^3, \tag{1}$$

where D^c is the collisional kinetic coefficient, D^R and D^{BB} are the radiative kinetic coefficients.

The temperature is found using the RRL radiation ratio as follows I_{Hn}^{peak}/I_c, where I_{Hn}^{peak} is the RRL peak intensity, I_c is the continuum intensity at the same frequency.

$$T_e = \nu^2 \left[\frac{(1-\beta_n)b_n}{T_e}\right] \frac{I_c^2}{2I_{Hn}^{peak}} \cdot \frac{1.9\cdot 10^2}{(\Delta n)^{1.85}} \cdot \frac{1}{3.14\cdot 10^{-2}\ln(10^6/20.18\nu)}, \qquad (2),$$

where ν is the radiation frequency (GHz), $\frac{(1-\beta_n)b_n}{T_e}$ is the coefficient as function of the Seaton matrix A_{n1} and the quantum numbers $n1$ and n; I_c is the continuum radiation intensity at the frequency ν; I_{Hn}^{peak} is the RRL radiation intensity; Δn describes the high order line number in the following way $\Delta n = 1, 2, 3, 4$ and 5 for $H_{n\alpha}, H_{n\beta}, H_{n\gamma}, H_{n\delta}$ and $H_{n\varepsilon}$. If the RRL number n is more than $n1$, term (1) is changed for solution in the form

$$\frac{(1-\beta_n)b_n}{T_e} = \frac{n^2(1-3/n)}{1.58\cdot 10^5}\frac{\exp(-(n1/n)^2)}{(A_{n1}+\pi)(n/n1)^5}, \qquad (3)$$

where A_{n1} and $n1$ are the Seaton matrix and the quantum number determined from relations (3).

The magnitude of the number $n1$ can be found experimentally by comparison of high orders RRL intensities at the nearest frequencies. Using formula (3) the number $n1$ is found fron the following relation

$$\frac{I_{Hm1}}{I_{Hm2}}\left(\frac{\Delta m1}{\Delta m2}\right)^{1.85}\left(\frac{m1}{m2}\right)^3 = \exp\left[-(n1)^2\left[\frac{1}{m1}-\frac{1}{m2}\right]\right], \qquad (4)$$

where $m1, m1+\Delta m1$ are the numbers corresponded to the two atomic levels of RRL; I_{Hm1} is the hydrogenic RRL intensity as function of the number $m1$.

According to formula (4) the number $n1$ is determined as function of the RRL radiation intensity. When the number $n1$ is found it is easy to calculate the density N_e by the method of the equation as following

$$\frac{d}{dn}(1-\beta_n)\,|_{n=n1} = 0. \qquad (5)$$

The collisional coefficient equals $D_n^c = 1.88\cdot 10^{-14} N_e T_e^{-1/2} n^7$.

The density N_e is determined from

$$N_e = \frac{(A_{n1}+\pi)}{1.88\cdot 10^{-14} n1^7} T_e^{1/2}, \qquad (6)$$

For some analysis the plasma temperature and the density are calculated by the ratio of $H_{56\delta}$ and $H_{60\varepsilon}$ intensities when the RRL numbers n is $n \le n1$. For these estimations the experimental data is chosen following the work by Gordon & Walmsley (1990). These are HII regions of W3, W49, DR21, which are studied.

References

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