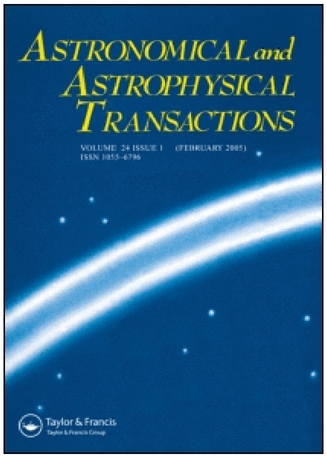

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ON THE BLUE SHIFT OF RADIORECOMBINATION LINES TOWARDS CAS A

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The radiorecombination line shift towards CASA and possible interpretation are considered

KEY WORDS Radio recombination lines, Zeeman effect, Interstellar medium

1. INTRODUCTION

One of the remarkable achievements in the radio recombination line (RRL) research of the last decade was the discovery of very low frequency carbon absorption RRL by Konoalenko and Sodin (1980) and Blake *et al.* (1980). Up to now, many lines have been observed in the spectrum of Cas A, from the emission line 166α to the absorption line 768α. A unique information about electron temperature and density has been obtained. Shaver (1990) noted, after Payne *et al.* (1989), that there is a puzzling blue shift of the absorption lines relative to the emission ones. In this report a theory of the RRL blue shift due to the diamagnetic Zeeman effect is developed and another possible interpretation is discussed.

2. DIAMAGNETIC ZEEMAN EFFECT FOR THE RYDBERG STATES

The Rydberg atom Hamiltonian in magnetic field B is given by

$$H = H_0 + H_1, H_2; \qquad H_1 = \frac{e\hbar}{2mc} \cdot \mathbf{B}(\mathbf{L} + 2\mathbf{S}); \qquad H_2 = \frac{e^2B^2}{8mc^2} r^2 \sin^2\theta; \qquad (1)$$

where H_0 is the atomic Hamiltonian, e and m are the electron charge and mass, $\mathbf{L}$ and $\mathbf{S}$ are the orbital and spin moments of the atom, $\mathbf{r}$ is radius-vector of the atomic electron, θ is the angle between $\mathbf{r}$ and $\mathbf{B}$, and c is the speed of light. The term H_1 is responsible for the linear Zeeman effect giving splitting of the atomic levels without shifting them, H_2 is the diamagnetic part of the atom interaction with the magnetic field. In usual spectroscopy (for a small principal quantum number n), H_2 is negligible. H_2 increases with n in proportion to n^4, and this term becomes significant for the Rydberg states.

The general problem of the eigenvalues of the Hamiltonian (1) is rather complicated even in first order of perturbation theory (see, e.g., Braun, 1983). A level with the principal quantum number n splits into $n/2$ sublevels, and the problem reduces to the diagonalization of matrixes of the dimension $\sim(n/2) \times (n/2)$. We are interested in the average shift of the level n. This is given by the trace of the matrix H_2 and is independent of the chosen representation. In the unperturbed hydrogen function representation, the average shift of the level n is

$$\delta E_n = \frac{e^2B^2}{8mc^2}\frac{1}{n}2 \cdot \sum \langle nlm|\, r^2 \sin^2\theta \,|nlm\rangle = \frac{e^2B^2}{48mc^2} a_0^2 n^2(7n^2+5), \qquad (2)$$

where a_0 is the Bohr radius. The blue shift of the line $n - n + dn$ is $\left(\frac{d}{dn}\delta E_n\right)\Delta n$, and the relative shift $\delta\omega/\omega$ is equal to

$$\frac{\delta\omega}{\omega} = \frac{1}{\Delta E} \cdot \left(\frac{d}{dn}\delta E_n\right)\Delta n \cong \frac{7}{12}\alpha^2\left(\frac{B}{B_0}\right)^2 n^6, \qquad (3)$$

where $\alpha = 1/137$ is the fine structure constant, $B_0 = 1.7 \cdot 10^7$ Gauss is the atomic unit of magnetic field. The corresponding Doppler velocity is

$$\delta v = 0.3 \cdot 10^5 \cdot (n/1000)^6 B^2 \text{ km/s/Gauss}^2. \qquad (4)$$

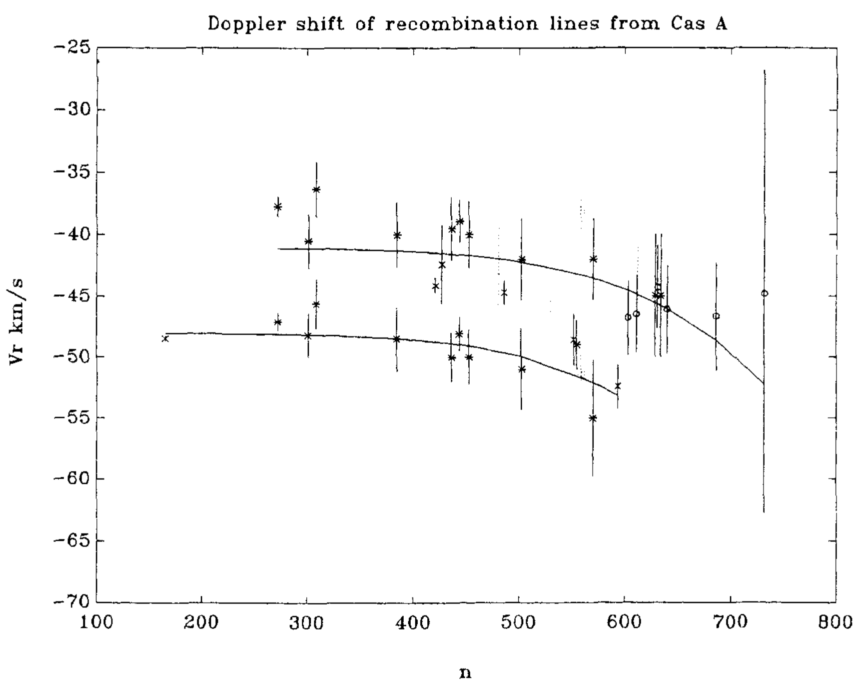

Figure 1 The shift of the recombination lines as a function of the principal quantum number n. Observational data: of Payne *et al.* (1989) and Anantharanaiah *et al.* (1985) are shown by asterisks; Lekht *et al.* (1989), Ershov *et al.* (1987, 1984), and Sorochenko and Walmsley (1991), by crosses; and Konovalenko (1984), by circles. The dependence predicted for the "diamagnetic Zeeman effect", Eq. (4), is shown by solid line. The upper and lower curves correspond to $B = 0.05$ and 0.06 G, respectively.

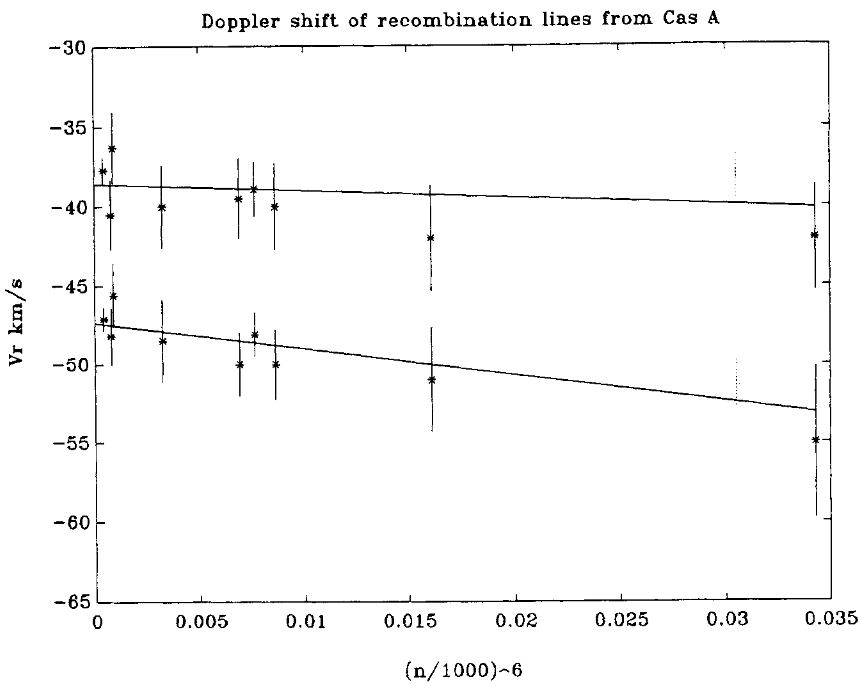

Figure 2 The shift of the recombination lines as a function of n^6. Observational data of Payne *et al.* (1989) are shown. Solid lines illustrate the "diamagnetic Zeeman effect" shift (4) for $B = 0.04$ G (upper curve) and $B = 0.07$ G (lower curve).

Comparison of the theory with observations (Payne *et al.*, 1989; Lekht *et al.*, 1984; Konovalenko, 1984; Ershov *et al.*, 1984, 1987; Anantharamiah *et al.*, 1985; Sorochenko and Walmsley, 1991) is illustrated by Figure 1. The velocity v and magnetic field B have been obtained with the help of the least-square fitting. Figure 2 shows similar results (scaled to $\sim n^6$) for the observations of Payne *et al.* (1989) alone. Of course, the errors are large, but the dependence on n (particularly for the lower curve) is pronounced. The derived values of the magnetic field are unreasonably large. In particular, for the $\Delta m = \pm 1$ transitions the linear Zeeman splitting is significantly larger than the diamagnetic shift.

3. DISCUSSION

Shaver (1990) suggested that the blue shift is associated with the RRL of heavy elements (for example, iron). However, Figures 1 and 2 show that the shift smoothly depends on n. Therefore, this interpretation is hardly reasonable. The blue shift in planetary nebulae can be explained by an expansion velocity increasing with radius. Since the interstellar medium toward Cas A is optically thin, this interpretation is inconsistent either.

Consider now possible physical explanations. First, this is the quadratic Stark effect: collisions with slow charged particles give the electric fields which shift the Rydberg states. However, then the ionization energy increases and, because higher levels are perturbed stronger, the corresponding spectral lines are red-shifted. Another reason might be the line shift due to nonthermal radio background in the interstellar medium. The theory of the Rydberg level shift in the external radiation field has been developed by Beigman (1991). The RRL shift is blue, but very weak. The interpretation involving the diamagnetic Zeeman effect is consistent with available observations, but the resulting magnetic field estimate is too high. In addition, there is a problem with $\Delta m = 1$ transitions. At low frequency they produce rather broad and weak lines which, however, may be unobservable. The linear Zeeman splitting of the 21 cm line represents a more difficult problem deserving a special analysis. Possibly, the RRL arise not in the interstellar clouds, but within the cold regions upstream the shock wave of Cas A.

We note that the proposed interpretation of the blue shift requires very high polarization of the RRL (with the electric vector directed along the magnetic field). Thus, polarization measurements of the RRL are the *experimentum crucis* for the "diamagnetic" interpretation.

Anyway, the blue shift problem of the low frequency RRL deserves further studies and new observational and theoretical investigations are needed.

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