IRAMP
13(2), July 2022, pp. 87-92

ISSN: 2229-39-44

Are Hydrogen Column Densities in Galactic Dark Matter Halos Overestimated?

E. OKS

Physics Department, 380 Duncan Drive, Auburn University, Auburn, AL 36849, USA

ABSTRACT: Emission of hydrogen atoms has been observed in dark matter halos of a number of galaxies. We discuss how the hydrogen column densities in these astrophysical objects can be determined. Specifically we study how the determination of the column density of hydrogen atoms from the observed astrophysical data would be affected by the possible presence of the Second Flavor of Hydrogen Atoms (SFHA), whose existence had been previously proven in four different types of atomic experiments and had helped explaining two puzzling astrophysical observations: the anomalous absorption in the 21 cm line from the early Universe and the smoother, less clumpy distribution of dark matter in the Universe than predicted by the Einstein's gravity. By a model example we demonstrate that the neglect of the SFHA leads to the overestimation of the column density of hydrogen atoms in dark matter halos by about 30%.

KEYWORDS: galaxies: haloes; galaxies: fundamental parameters; galaxies: photometry; (cosmology:) dark matter; cosmology: observations; cosmology: theory

1. INTRODUCTION

The HI regions in dark matter halos of a number of galaxies have been observed – see, e.g., Peters et al (2017a, 2017b) papers, Benitez-Llambay et al (2017) paper, Peters (2014) dissertation, and references therein. Peters et al (2017a, 2017b) and Peters (2014) pointed out that each of the eight galaxies that they analyze has approximately the same maximum surface brightness temperature throughout its disc. They explained this phenomenon by the self-absorption in the hydrogen line 21 cm.

The opacity or absorption coefficient τ_ν is controlled by the column density N_H of hydrogen atoms and their spin temperature T_{spin}. The relation between the brightness in the temperature scale T_B and the opacity is (see, e.g., Draine (2011), Eq. (7.26)):

$$T_B = T_{spin}\{1 - \exp[-\tau_\nu(N_H, T_{spin})]\}. \tag{1}$$

Equation (1) allows determining the column density N_H from the observed T_B and the assumed or estimated T_{spin} (e.g., Peters et al (2017a) and Peters (2014) assumed T_{spin} = 100 K).

In the present paper we analyze how the determination of the column density would be affected by the presence of the Second Flavor of Hydrogen Atoms (SFHA) in the mixture with the usual hydrogen atoms in these HI regions. So, let us first briefly remind what the SFHA is.

There are two solutions of the standard Dirac equation of quantum mechanics for hydrogen atoms. At a small distance r from the origin, one solution (which is commonly used) is weakly singular, while the other solution is singular more strongly. Oks (2001) showed that with the allowance for the fact that the experimental charge distribution inside protons has the peak at the origin (see, e.g., Simon et al (1980) and Perkins (1987)), the second (strongly singular) solution outside the proton can be tailored with the (regular) solution inside the proton and thus becomes legitimate, but only for the states of the zero orbital momentum, i.e., for the S-states. This second type of hydrogen atoms possessing only the S-states (of the same energies as in the case the usual hydrogen atoms described by the first solution of the Dirac equation, thus manifesting an additional degeneracy) was later named the Second Flavor of Hydrogen Atoms (SFHA): by the analogy with the quantum chromodynamics where up and down quarks are named two flavors (Oks, 2020a).

In virtue of possessing only the S-states and in accordance to the quantum-mechanical selection rules, the SFHA do not absorb or emit the electromagnetic radiation (except the 21 cm line): the SFHA are dark. This is the primary distinction of the SFHA from the usual hydrogen atoms.

By now the existence of the SFHA has been proven in four different types of atomic experiments, as specified below.

A. Experimental distribution of the linear momentum in the ground state of hydrogen atoms.

Before year 2001, there was a long-standing, huge discrepancy between the High-energy Tail of the linear Momentum Distribution (HTMD), deduced from the analysis of atomic experiments (Gryzinski (1965)) and the theoretical HTMD, calculated by Fock (1935). The discrepancy reached many ordered of magnitude – three or four orders of magnitude – in the relevant range of the linear momentum p (Oks (2001)).

This huge discrepancy got completely removed by engaging the SFHA. This was achieved due to the very different behavior of the coordinate wave function ø(r) of the SFHA at small r, compared to the usual hydrogen atoms, and therefore to the significantly different behavior of the SFHA wave function in the momentum representation ö(p) at large p, compared to the usual hydrogen atoms (Oks, 2001). We remind that ø(r) and ö(p) are related by the Fourier transform.

B. Experiments on the electron impact excitation of hydrogen atoms

The theoretical ratio of the cross-section σ_{2S} of the excitation for the state 2s to the cross-section σ_{2P} of the excitation of the state 2S turned out to be systematically higher than the experimental ratio *by about 20%* (far beyond the experimental error margins of 9%), as follows from papers by Callaway & McDowell (1983) and by Whelan et al (1987).

The experimental cross-section σ_{2S} for the excitation to the 2S state was measured by the quenching technique: an electric field was applied for intermixing the states 2S and 2P and then detecting the emission of the Lyman-alpha line from the state 2P to the ground state. However, in the experimental hydrogen gas, the applied electric field can mix the state 2S with the state 2P (thus causing the subsequent by emission of the Lyman-alpha line) only for the usual hydrogen atoms. Indeed, since the SFHA has only the S-states, they do not contribute to the observed Lyman-alpha signal. Consequently, the experimental determination of the cross-section σ_{2S} by the quenching technique should underestimate this cross-section compared to its actual value. At the same time, the cross-section σ_{2P} should not be affected by the presence of the SFHA. In Oks (2022a) paper it was demonstrated that the above 20% can be removed if in the experimental hydrogen gas, both the SFHA and the usual hydrogen atoms were present in about equal shares.

C. Experiments on the electron impact excitation of hydrogen molecules

There was a discrepancy *by at least a factor of two* between the experimental and theoretical cross-sections. In Oks (2022b) paper it was shown that this discrepancy can be removed if the SFHA was present in the experimental gas of hydrogen molecules.

D. Experiments on the charge exchange between hydrogen atoms and protons

There is a significant discrepancy between the experimental and theoretical cross-sections In Oks (2021a) paper it was demonstrated that this discrepancy can be eliminated if the SFHA was present in the experimental gas.

The SFHA became a candidate for dark matter or at least for a part of it, as explained below. Bowman et al (2018) reported an anomalous absorption in the redshifted 21 cm spectral line from the early Universe. The observed amplitude of the absorption profile of the 21 cm line was *by a factor of two greater* than calculated by the standard cosmology. This dramatic discrepancy indicated that the gas temperature of the hydrogen in the early Universe was in fact significantly smaller than predicted by the standard cosmology.

Barkana (2018) brought up a hypothesis that some unspecified dark matter played the role of the cooling agent: it cooled the hydrogen gas via collisions. For the quantitative explanation of Bowman et al (2018) observation, the mass of these unspecified dark matter particles should not have exceeded 4.3 GeV, according to Barkana (2018).

Subsequently, McGaugh (2018) came to an important conclusion while analyzing the papers by Bowman et al (2018) and Barkana (2018). Namely, the Bowman et al (2018) results represented an *unambiguous proof that dark matter is baryonic*. Consequently, theories introducing non-baryonic nature of dark matter have to be discarded – since only baryonic dark matter was capable of providing the required additional cooling to the hydrogen gas (McGaugh (2018)).

In Oks (2020b) paper the following question has been considered: what if the unspecified baryonic dark matter, suggested by Barkana (2018) as the cooling agent, was actually the SFHA? In Oks (2020b) paper it was expounded that, the SFHA, being decoupled from the Cosmic Microwave Background radiation (CMB) in the course of the Universe expansion, cool down quicker than the usual hydrogen atoms (the latter decoupling from the CMB much later). Therefore, the SFHA spin temperature, controlling the intensity of the absorption signal in the 21 cm line, is lower thank for the usual hydrogen atoms. In that paper it was demonstrated that this explains the anomalous absorption in the 21 cm line, observed by Bowman et al (2018), both qualitatively and quantitatively.

One of the alternative explanations introduced some exotic, never discovered dark matter particles of the charge of the million times smaller than the charge of the electrons, as in paper by Muñoz & Loeb (2018). However, even after introducing these never discovered particles, Muñoz & Loeb (2018) estimated these particles could constitute only ~ 10 per cent or less of all of the dark matter. We also emphasize that the SFHA-based explanation does not require an extra assumption of some additional radio background proposed by Feng & Holder (2018) and by Ewall-Wice et al (2018).

Besides, there is another perplexing astrophysical observation that can be explained based on the SFHA. The most detailed map of the distribution of dark matter in the Universe, created recently by the Dark Energy Survey team, demonstrated that the distribution of dark matter is by few percent smoother, less clumpy than the expectations based on the Einstein’s gravity (Jeffrey et al (2021)). This puzzling observation induced calls for new physical laws.

Oks (2021b) explained this perplexing observation without invoking any new physical laws. In that paper it was demonstrated that if dark matter is represented by the SFHA, then in a minor part of the ensemble of the SFHA, there occur gravitationally interacting pairs of the SFHA. Atoms within the pair would gradually come closer to each other due to the gradual loss of the energy. However, at some point of this process, quantum effects would terminate this “clumping”. This explained Jeffrey et al (2021) observation both qualitatively and quantitatively.

In the present paper we study how the fact that the spin temperature of the SFHA is lower than for the usual hydrogen atoms, would affect the determination of the column density of hydrogen atoms in the mixture of both types of atoms in the HI regions of dark matter haloes. We show that disregarding the presence of the SFHA leads to the overestimation of the column density by about 30%.

2. REVISED ESTIMATES OF THE HI COLUMN DENSITY

By combining Eqs. (8.8) and (8.11) from Draine (2011) book (see also Peters (2014)), the absorption coefficient τ_ν (N_H, T_{spin}) can be expressed as follows

$$\tau_\nu(N_H, T_{spin}) = 2.190\ (2\pi)^{1/2} N_H/T_{spin}, \tag{2}$$

where N_H is in units of 10^{21} cm^{-2} and T_{spin} is in units of 100 K. On substituting Eq. (2) in Eq. (1), we get (in case where the SFHA would be disregarded):

$$T_B = T_{spin}\{1 - \exp[-2.190\ (2\pi)^{1/2} N_H/T_{spin}]\}. \tag{3}$$

We remind that T_{spin} is the spin temperature of the usual hydrogen atoms.

The spin temperature T_{spin2} of the SFHA is lower than T_{spin}, as explained in Oks (2020a) paper. The ratio T_{spin2}/T_{spin} should be about the same as the corresponding ratio of the kinetic temperatures T_{K2}/T_K, the latter being equal to 3/4, according to the calculations from Oks (2020b) paper. So, we set below $T_{spin2}/T_{spin} = 3/4$.

As an example, we consider a mixture of 84% of the SFHA and 16% of the usual hydrogen atoms, corresponding to the observed ratio of the dark and ordinary matter. The expression for the brightness temperature of this mixture takes the form:

$$T_B = T_{spin}\{1 - \exp[-2.190\ (2\pi)^{1/2}N_H(0.16/T_{spin} + 0.84/T_{spin2})]\} = T_{spin}\{1 - \exp[-2.80\ (2\pi)^{1/2}N_H/T_{spin}]\}. \tag{4}$$

According to Peters et al (2017a, 2017b) and Peters (2014), the observed brightness temperature was $T_B = 90$ K. As for the spin temperature T_{spin} of the usual hydrogen atoms, they assumed it to be 100 K, but noted that it was the assumption “based purely on what seemed to work best” in their calculations. So, in reality, T_{spin} could differ from 100 K. Therefore, below we consider values of T_{spin} in the range from 100 K to 150 K.

Figure 1 shows the three-dimensional plot of the dependence of the column density N_H on the spin temperature T_{spin} of the usual hydrogen atoms and on the brightness temperature T_B for two scenarios. The upper surface, obtained from Eq. (3), corresponds to the neglect of the SFHA. The lower surface, obtained from Eq. (4), corresponds to the allowance for the SFHA. It is seen that in the case where the SFHA is neglected, there is always an overestimation of the column density N_H.

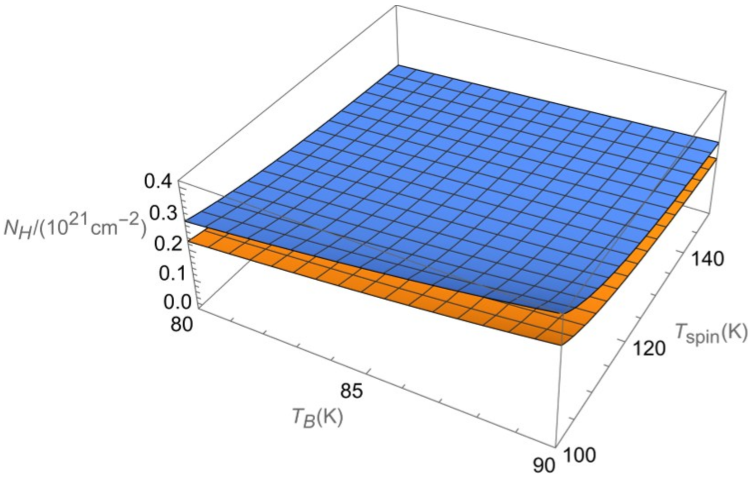

Fig. 1. Dependence of the column density N_H on the spin temperature T_{spin} of the usual hydrogen atoms and on the brightness temperature T_B for two scenarios. The upper surface corresponds to the neglect of the SFHA. The lower surface corresponds to the allowance for the SFHA.

Now we fix the brightness temperature at the observed value $T_B = 90$ K (according to Peters et al (2017a, 2017b) and Peters (2014)), and solve Eqs. (3) and (4) with respect to the column density N_H for the values of T_{spin} from 100 K to 150 K. The results are presented in Fig. 2. The solid line corresponds to the allowance for the SFHA and the dashed line corresponds to the case, where the SFHA would be disregarded.

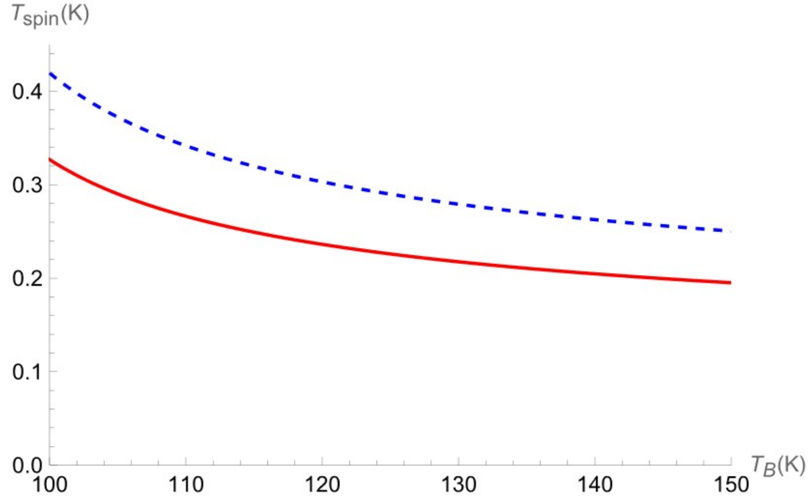

Fig. 2. The hydrogen column density N_H versus the spin temperature T_{spin} of the usual hydrogen atoms for the brightness temperature T_B = 90 K. The solid line corresponds to the allowance for the SFHA and the dashed line corresponds to the case, where the SFHA would be disregarded.

It is seen that the neglect of the SFHA leads to the overestimation of the column density N_H by about 30%.

4. CONCLUSIONS

We discuss how the column density of hydrogen atoms in the HI regions, observed in dark matter halos of a number of galaxies (see, e.g., Peters et al (2017a, 2017b) and Peters (2014)), can be determined. Specifically, we studied how the determination of the column density from the observed astrophysical data would be affected by the possible presence of the SFHA, whose existence had been previously proven in four different types of atomic experiments and had helped explaining puzzling astrophysical observations by Bowman et al (2018) and by Jeffrey et al (2021). In the model example we demonstrated that the neglect of the SFHA leads to the overestimation of the column density of hydrogen atoms in dark matter halos by about 30%.

References

1. Barkana. R. 2018, Nature, 555, 71
2. Benitez-Llambay, A. et al 2017, MNRAS, 465, 3913
3. Bowman, J.D., Rogers, A.E.E., Monsalve, R.A., Mozdzen, T.J., & Mahesh, N. 2018, Nature, 555, 67
4. Callaway, J., & McDowell, M.R. C. 1983, Comments At. Mol. Phys., 13, 19
5. Draine B. T., 2011, Physics of the Interstellar and Intergalactic Medium (Princeton: Princeton Univ. Press)
6. Ewall-Wice, A., Chang, T.-C., Lazio, J., , Doré, O., Seiffert, M., & Monsalve, R.A. 2018, ApJ 868, 63
7. Feng, C., & Holder, J. 2018, ApJ, 858, L17
8. Fock, V. 1935, Z. Physik 98, 145
9. Gryzinski, M. 1965, Phys. Rev., 138, A336
10. Jeffrey, N. et al. 2021, MNRAS, 505, 4626
11. McGaugh, S.S. 2018, Research Notes of the Amer. Astron. Soc., 2, 37
12. Muñoz, J.B., & Loeb, A. 2018, Nature, 557, 684
13. Oks, E. 2001, J. Phys. B: At. Mol. Opt. Phys., 34, 2235
14. Oks, E. 2020a, Atoms, 8, 33
15. Oks, E. 2020b, Research in Astronomy and Astrophysics, 20, 109
16. Oks, E. 2021a, Foundations, 1, 265

17. Oks, E. 2021b, Research in Astronomy and Astrophysics, 21, 241
18. Oks, E. 2022a, Foundations, 2, 541
19. Oks, E. 2022b, Foundations, 2, 697
20. Perkins, D.H. 1987, Introduction to High Energy Physics (Menlo Park, CA: Addison-Wesley) Sect. 6.5.
21. Simon, G., Schmitt, Ch., Borkowski, F., & Walther, V.H. 1980, Nucl. Phys., A333, 381
22. Peters, S. P. C. 2014, PhD thesis, Univ. Groningen. http://irs.ub.rug.nl/ppn/380637316
23. Peters, S.P.C., van der Kruit, P.C., Allen, R.J., & Freeman, K.C. 2017a, MNRAS, 464, 2
24. Peters, S.P.C., van der Kruit, P.C., Allen, R.J., & Freeman, K.C. 2017b, MNRAS, 464, 65
25. Whelan, C.T., McDowell, M.R.C., & Edmunds, P.W. 1987, J. Phys. B: At. Mol. Phys., 20, 1587