Research in Astronomy and Astrophysics, 23:035011 (4pp), 2023 March https://doi.org/10.1088/1674-4527/acbae9

Galactic Dark Matter Halos Containing H I Regions: A Possible Overestimation of the Column Densities

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Received 2022 December 9; accepted 2022 December 30; published 2023 February 28

Abstract

We analyze how the column density of hydrogen atoms in the H I regions, observed in dark matter halos of a number of galaxies, 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 demonstrated in four different types of atomic experiments and had helped in 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 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%. We perform these relatively simple estimates just to get the message across and to motivate further corresponding theoretical and experimental studies.

Key words: galaxies: halos – galaxies: fundamental parameters – galaxies: photometry – (cosmology:) dark matter – cosmology: observations – cosmology: theory

1. Introduction

The existence of H I regions in dark matter halos of a number of galaxies is an observational fact—see, e.g., Peters et al. (2016a, 2016b), Benítez-Llambay et al. (2016), the Peters (2014) dissertation and references therein. Peters et al. (2016a, 2016b) and Peters (2014) pointed out that each of the eight galaxies that they analyzed has approximately the same maximum surface brightness temperature throughout its disk. They explained this phenomenon by self-absorption in the hydrogen 21 cm line.

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

$$T_B = T_{\rm spin}(1 - \exp(-\tau_\nu(N_{\rm H}, T_{\rm spin}))). \quad (1)$$

Equation (1) allows determining the column density $N_{\rm H}$ from the observed T_B and the assumed or estimated $T_{\rm spin}$ (e.g., Peters et al. 2016a and Peters 2014 assumed $T_{\rm spin} = 100$ 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 a mixture with the usual hydrogen atoms in these H I 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 more strongly singular. Oks (2001) showed that allowing for the fact that the experimental charge distribution inside protons has its 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 states with zero orbital angular momentum, i.e., for the S-states. This second type of hydrogen atom possessing only S-states (with the same energies as in the case of 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 analogy with quantum chromodynamics where up and down quarks are named two flavors (Oks 2020a).

By virtue of possessing only the S-states and in accordance with the quantum-mechanical selection rules, the SFHA does not absorb or emit electromagnetic radiation (except the 21 cm line), so the SFHAs are dark. This is the primary distinction between SFHA and usual hydrogen atoms.

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

A. Experimental distribution of 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 (Gryziński 1965) and the theoretical HTMD, calculated by Fock (1935). The discrepancy reached many orders of magnitude—three or four orders of magnitude—in the relevant range of 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 $\psi(r)$ of the SFHA at small r, compared to usual hydrogen atoms, and therefore to the significantly different behavior of the SFHA wave function in the momentum representation $\varphi(p)$ at large p, compared to usual hydrogen atoms (Oks 2001). We are reminded that $\psi(r)$ and $\varphi(p)$ are related by a 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 2 s 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 reported in Callaway & McDowell (1983) and 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 Lyα 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 emission of the Lyα line) only for the usual hydrogen atoms. Indeed, since SFHAs have only S-states, they do not contribute to the observed Lyα 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), it was demonstrated that the above 20% can be removed if in the experimental hydrogen gas, both the SFHAs 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), 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), 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 that calculated by standard cosmology. This dramatic discrepancy indicated that the gas temperature of hydrogen in the early Universe was in fact significantly smaller than that predicted by standard cosmology.

Barkana (2018) proposed 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 the 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 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 the 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) 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) it was expounded that the SFHA, being decoupled from the cosmic microwave background (CMB) radiation in the course of the Universe expansion, cools down more quickly than the usual hydrogen atoms (with 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 than 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 with a charge a million times smaller than the charge of electrons, as in Muñoz & Loeb (2018). However, even after introducing these never discovered particles, Muñoz & Loeb (2018) estimated these particles could constitute only ∼10% or less of all 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).

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 a few percent smoother and less clumpy than the expectations based on 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 exist gravitationally interacting pairs of the SFHA. Atoms within the pair would gradually come closer to each other due to the gradual loss of energy. However, at some point in this process, quantum effects would terminate this “clumping.” This explained the 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 that for usual hydrogen atoms, which would affect determination of the column density of hydrogen atoms in the mixture of both types of atoms in H I regions of dark matter halos. We show that disregarding the presence of the SFHA leads to overestimation of the column density by about 30%.

2. Revised Estimates of the H I Column Density

By combining Equations (8.8) and (8.11) from Draine (2011) (see also Peters 2014), the absorption coefficient $\tau_\nu(N_H, T_{spin})$ can be expressed as follows

$$\tau_\nu(N_H, T_{spin}) = 2.190\sqrt{2\pi}\frac{N_H}{T_{spin}}, \tag{2}$$

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

$$T_B = T_{spin}\left(1 - \exp\left(-2.190\sqrt{2\pi}\frac{N_H}{T_{spin}}\right)\right). \tag{3}$$

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

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

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

$$\begin{aligned} T_B &= T_{spin}\left(1 - \exp\left(-2.190\sqrt{2\pi}N_H\left(\frac{0.16}{T_{spin}} + \frac{0.84}{T_{spin2}}\right)\right)\right)\\ &= T_{spin}\left(1 - \exp\left(-2.80\sqrt{2\pi}\frac{N_H}{T_{spin}}\right)\right)\end{aligned}. \tag{4}$$

According to Peters et al. (2016a, 2016b) 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 an 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 to 150 K.

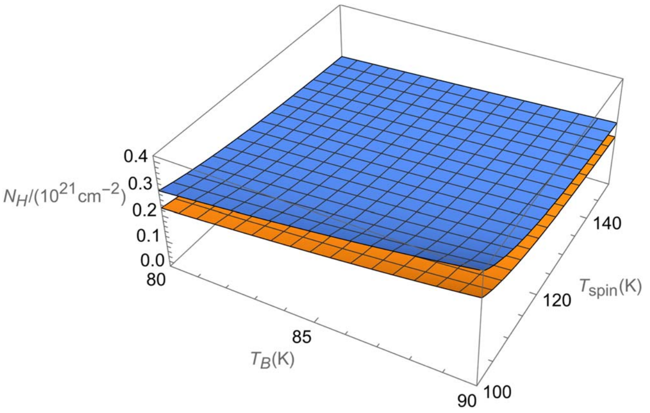

Figure 1. Dependence of the column density N_H on the spin temperature T_{spin} of the usual hydrogen atoms and on the brightness temperature T_B for two scenarios. The upper surface corresponds to neglecting the SFHA. The lower surface corresponds to allowing for the SFHA.

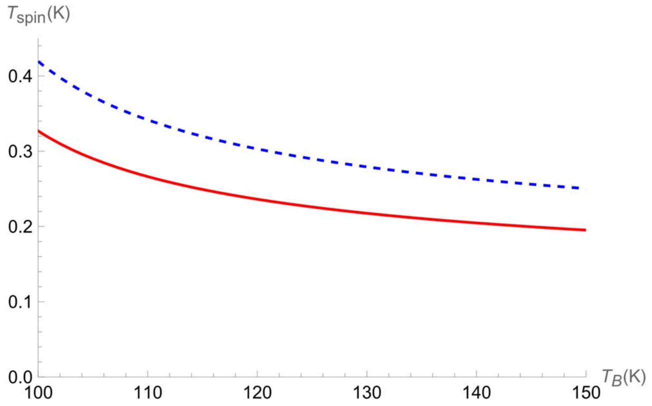

Figure 2. The hydrogen column density N_H vs. the spin temperature T_{spin} of the usual hydrogen atoms for the brightness temperature $T_B = 90$ K. The solid line corresponds to allowing for the SFHA and the dashed line corresponds to the case where the SFHA would be disregarded.

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 Equation (3), corresponds to neglecting the SFHA. The lower surface, obtained from Equation (4), corresponds to allowing 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.

Now we fix the brightness temperature at the observed value $T_B = 90$ K (according to Peters et al. 2016a, 2016b and Peters 2014), and solve Equations (3) and (4) with respect to the column density N_H for the values of T_{spin}

from 100 to 150 K. The results are presented in Figure 2. The solid line corresponds to allowing for the SFHA and the dashed line corresponds to the case where the SFHA would be disregarded.

It is seen that neglecting the SFHA leads to overestimation of the column density N_{H} by about 30%.

3. Conclusions

We analyzed how the column density of hydrogen atoms in the H I regions, observed in dark matter halos of a number of galaxies (see, e.g., Peters et al. 2016a, 2016b and Peters 2014), can be determined. Specifically, we studied how the determination of the column density from observed astrophysical data would be affected by the possible presence of the SFHA, whose existence had been previously demonstrated in four different types of atomic experiments and had helped in explaining puzzling astrophysical observations by Bowman et al. (2018) and Jeffrey et al. (2021). In the model example, we demonstrated that neglecting the SFHA leads to overestimation of the column density of hydrogen atoms in dark matter halos by about 30%.

Our estimates are relatively simple. We performed them just to get the message across and to motivate further corresponding theoretical and experimental studies.

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