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The Case for Cold Hydrogen Dark Matter

Eugene Terry Tatum

Abstract

The novel 'Cold Hydrogen Dark Matter' (CHDM) theory is summarized in this chapter. Special attention is paid to the fact that current technology prevents us from directly observing extremely cold ground state atomic hydrogen when it is of sufficiently low density in deep space locations. A number of very recent observations in support of this theory are summarized, including cosmic dawn constraints on dark matter. The importance of the Wouthuysen-Field effect as a probable mechanism for CMB decoupling of hydrogen at cosmic dawn is also stressed. This mechanism does not require a non-baryonic dark matter intermediary. Several predictions for this theory are made for the coming decade of observations and simulations.

Keywords: dark matter, CHDM, primordial hydrogen, cosmic dawn, Wouthuysen-Field effect, cosmology theory, Milky Way, galactic evolution, interstellar medium, hydrogen snow clouds

1. Introduction and background

This chapter will familiarize the reader with the author's 'Cold Hydrogen Dark Matter' (CHDM) theory and summarize a wealth of recent observational data in support of this theory. A discussion of a likely cosmic and galactic evolution scenario for primordial hydrogen will follow, and the chapter will end with several predictions for the coming decade of observations and simulations.

1.1 The theory

In May of 2019, the author was invited to attend a dark matter workshop as part of the World Science Festival. There he had the opportunity to present his CHDM theory to colleagues, after which the theory was published [1], and then first summarized in a chapter of IntechOpen's book entitled *Cosmology 2020 - The Current State* [2].

The theory holds that a certain deep space interstellar, circumgalactic, and intergalactic species of cold hydrogen can be particularly difficult to detect, much less accurately quantify. Specifically, extremely low density cold atomic hydrogen in its lowest ground state (i.e., ground state H I with anti-parallel electron spin) *cannot* emit light and does not collide sufficiently often with its neighboring atoms to create a luminous cloud readily visible from Earth or telescopic satellites. Furthermore, its deep space location vastly reduces its frequency of photon absorption that could be visible from Earth or satellites.

In light of this theory, it may seem paradoxical that a soft glow of H I line (21-cm) emissions can be readily detected throughout our Milky Way galaxy (MW) by radio astronomy [3, 4]. The ultrafine 21-cm line indicates a spin flip transition of the hydrogen electron in its ground state. The lower energy spin state is one in which the electron spin orientation is anti-parallel to the hydrogen nuclear spin orientation. Not surprisingly, 21-cm H I emissions are readily detectable in relatively dense and dynamic (cold, warm or hot) hydrogen clouds, which are particularly concentrated within the galactic bulge and the spiral arms of the disk. These 21-cm radio waves readily pass through dense galactic clouds which block most visible light. In fact, our knowledge of the number and distribution of the spiral arms of the MW and other galaxies is largely predicated on radio astronomy H I line mapping. However, while some of these H I emissions are undoubtedly coming from cold (i.e., slow-moving) hydrogen, that does not fully meet the author's definition of CHDM, precisely because it is relatively *concentrated* atomic hydrogen and, therefore, observable. To put it simply, not all cold hydrogen is dark. Only the very low density, lowest ground state, H I species near the cosmic micro-wave background (CMB) radiation temperature is dark.

When we make observations well away from the spiral arms, and along lines roughly perpendicular to the MW disc, it is estimated from spectral analysis that the vacuum density of deep interstellar space averages roughly one atom per cubic centimeter [5–7]. Similar observations in lines-of-sight to distant light sources have resulted in an average intergalactic vacuum density estimate of roughly one atom per cubic meter. According to the theory presented here, it is in these interstellar, circumgalactic and intergalactic deep space regions where the majority of the difficult-to-detect, extremely cold, and lowest density hydrogen (i.e., CHDM) must reside.

## 2. Observational support for the CHDM theory

2.1 MW observations and halo mass calculations

Posti & Helmi reported using *Gaia* data on globular cluster proper motions to calculate relative masses of dark matter and visible matter within a 20 kpc (65,200 light-years) radius halo sphere centered on the MW [8]. **Figure 1** shows this author's schematic representation of the Posti & Helmi sphere, according to their description.

This diagram is roughly to scale, since the MW disk has a radius of approximately 50,000 light-years and an average thickness of approximately 1,000 light-years. The halo is denoted in black, and the rare stars in the halo outside the disk and bulge are also schematically represented.

Posti & Helmi provided data which allow one to calculate a dark matter-to-visible matter ratio of 2.54 within their 20 kpc radius sphere. Normalizing the visible mass (in the form of stars, gas clouds and dust) of the MW disc and bulge to a current best estimate [9] of 250 billion ⊙ (solar masses), allows one to calculate a dark matter mass within the Posti & Helmi sphere of 635 billion ⊙. This number is obtained by multiplying 250 billion ⊙ by 2.54.

To compare the CHDM theory with these observations, one can assume that a great majority of the estimated single atoms per cubic centimeter of the 20 kpc halo sphere deep space are cold hydrogen atoms. This conservatively implies an average vacuum matter density of 1.67×10^{-21} kg.m^{-3} within a spherical volume of 9.85×10^{62} m^3. Multiplying these two numbers together gives a total halo vacuum mass of 1.645×10^{42} kg. This amounts to roughly 827 billion ⊙ within the halo
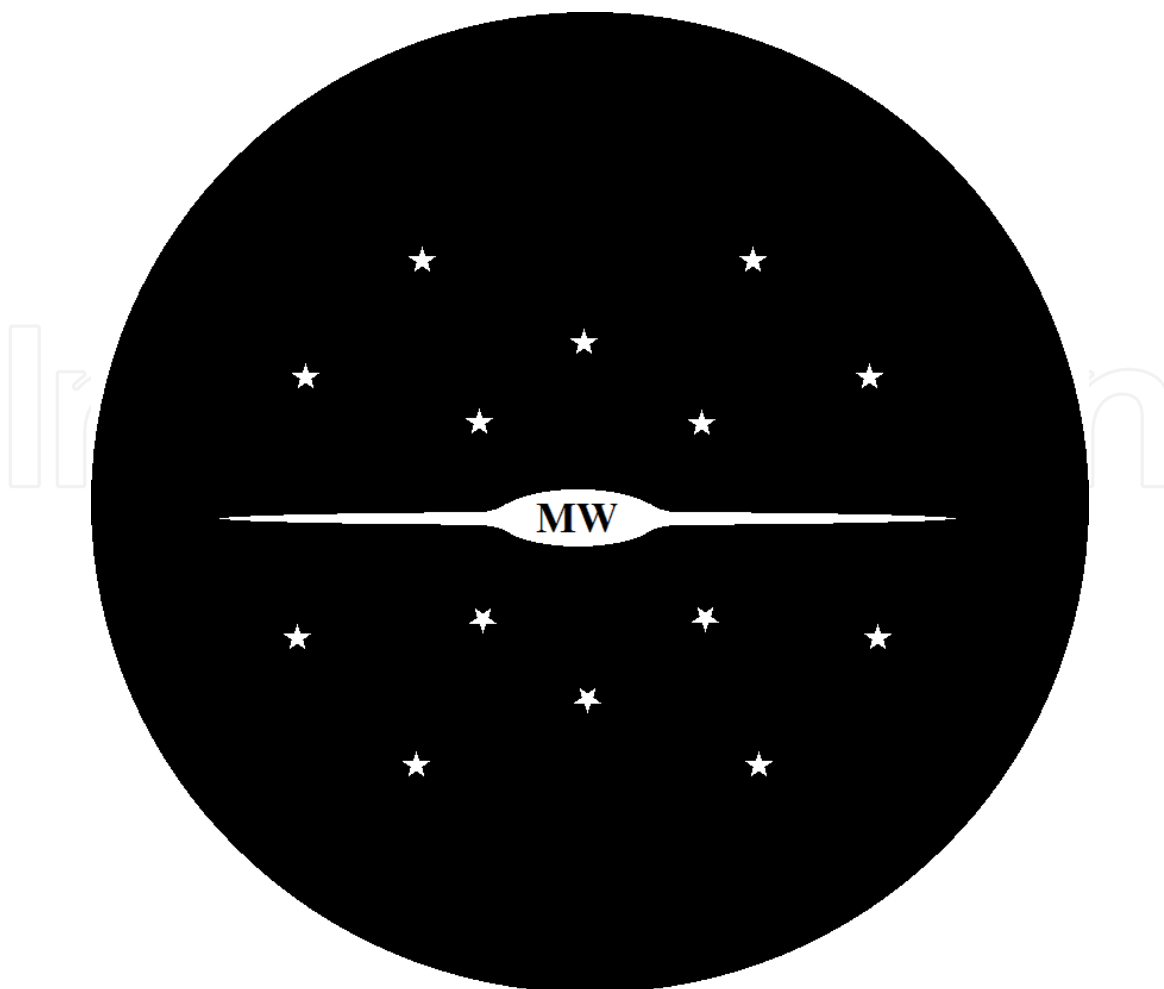
Figure 1.
Posti & Helmi 20 kpc halo sphere and MW galaxy.

vacuum *outside* the thin slice representing the visible galactic disk and bulge. This estimate is obtained by dividing 1.645 x 10^{42} kg by the solar mass of 1.989 x 10^{30} kg. Even allowing for only 0.77 such atoms per cubic centimeter of the halo outside the visible galaxy, the Posti & Helmi ratio of 2.54 can be met. This is because 827 billion $\odot$ multiplied by 0.77 is 636.8 billion $\odot$. So, an exceedingly low average halo vacuum density of approximately 0.77–1.0 hydrogen atom per cubic centimeter can *dwarf* the 250 billion $\odot$ of the visible MW stars, gas clouds, and dust! This makes the CHDM-defined species of atomic hydrogen a serious candidate for the 'missing matter' we are currently referring to as dark matter.

2.2 Cosmic Dawn observations of the redshifted H I line

The early cosmic dawn (reionization epoch) spin temperature of primordial neutral atomic hydrogen can be studied by measuring the redshifted 21-cm H I line at frequencies at or near 78 MHz. These line measurements (specifically '21-cm brightness temperatures') correspond to redshifts in the range of $15 < z < 20$. By performing this analysis in the EDGES study, Bowman, et al. [10] have accumulated a wealth of data on the temperature of cosmic dawn primordial hydrogen. They have determined that cosmic dawn hydrogen was temporarily chilled to the low single digits of the Kelvin scale, reaching a nadir at around $z = 17$ (about 180 million years after the big bang). Thus, primordial hydrogen during early cosmic dawn, from about 100–250 million years after the big bang, was temporarily *decoupled* from its usual equilibration with the CMB radiation. This is what made it *visible*.

Barkana [11] has used the Bowman data to *significantly* constrain the mass m_x of dark matter particles according to a baryon-dark matter (b-DM) particle interaction theory. This theory holds that, for *non-baryonic* dark matter to have interacted with baryonic matter in the early universe, it needed to *first* decouple from the CMB temperature, chilling to the point where it could *then* decouple primordial hydrogen from the CMB temperature.

Barkana's dark matter constraints are nicely graphed in Figure 3, page 9 of his review. This finding was a great disappointment to WIMP theorists, since the dark matter constraints effectively eliminate most, if not all, weakly-interactive massive particles. It *also* rules out baryons, except for atomic hydrogen, molecular hydrogen and perhaps He-3. This is because Barkana's dark matter constraints effectively rule out a dark matter particle much greater than 2–3 GeV, which strongly supports the case for atomic hydrogen!

To comprehend the significance of these dark matter constraints, the reader should scrutinize Figure 3 of [11]. They should pay particular attention to the dark matter particle mass m_x corresponding to a cross-section σ_1 value of 10^{-20} cm^2 and a 21-cm brightness temperature $\log_{10}$ value (in mK) of 2.32. Note that these values correspond to a cold dark matter particle matching neutral atomic hydrogen, with a similar low velocity scattering cross-section and a mass-energy of 0.938 GeV. Furthermore, it should be remembered that the redshifted cosmic dawn 21-cm H I line is the *signature* of atomic hydrogen in its ground state.

2.3 McGaugh's argument for a 'purely baryonic universe'

In March of 2018, around the time of the Bowman, et al. EDGES publication, physicist Stacy McGaugh published a brief note [12] which made a cogent and compelling argument for baryonic dark matter. He noted that the high intensity of Bowman's redshifted H I line was a problem for the standard model of cosmology assumption of a non-baryonic b-DM interaction at cosmic dawn. McGaugh correctly pointed out that current atomic theory would indicate such a signal has the maximum T_{21} intensity when the neutral hydrogen fraction X_{HI} is 1 and the spin temperature T_S is equal to the Kelvin temperature. Although McGaugh did not explicitly state that a primordial atomic hydrogen self-interaction (i.e., decoupled colder atomic hydrogen interacting with CMB-equilibrated atomic hydrogen) was a more reasonable explanation for the EDGES study results, his statement that these observations would be 'expected for a purely baryonic universe' clearly carried this implication. He made the point that a dark matter particle outside of the standard particle model (i.e., a non-baryonic particle) was unnecessary to explain the EDGES study findings.

2.4 A cosmic Dawn H I mechanism (the Wouthuysen-Field effect)

The Bowman, Barkana and McGaugh publications, while opening up the possibility for a light baryon to fit within the current dark matter constraints, did not clearly specify a mechanism by which a baryon could have decoupled primordial hydrogen from the cosmic dawn CMB temperature. However, as detailed in the author's original CHDM publications, those mysterious cold baryons could well have been the first of the primordial hydrogen atoms chilled by the first stars of cosmic dawn.

The first stars of cosmic dawn are believed to have been massive blue stars emitting a great deal of ultraviolet (UV) radiation, including Lyman-alpha (Lyα) waves. Anyone with a knowledge of UV radiation effects on atomic hydrogen would have learned of the Wouthuysen-Field effect (WFE) discovered in the 1950s [13].

In short, the author proposes that the WFE is the likely mechanism by which the first primordial hydrogen atoms were decoupled from the CMB during cosmic dawn. A non-baryonic intermediary would not have been required.

In the laboratory, Lyα radiation has the correct energy to trigger, by a multi-step process, the otherwise 'forbidden' transition (i.e., parallel to anti-parallel electron spin orientation) in ground state atomic hydrogen. As mentioned in the Introduction, the anti-parallel electron spin state has the lower energy level. This effect would have decoupled H I from the CMB temperature. Absorption and re-emission of Lyα photons effectively causes a redistribution of the balance between the 21-cm hydrogen ground states, such that a higher percentage of H I has its electron in the anti-parallel electron spin orientation with respect to the proton spin orientation. The net effect would have been to chill the Lyα-absorbing H I well below the CMB temperature and to make its redshifted ultrafine 21-cm line highly visible (whereas, CMB-equilibrated H I is *invisible* [14]).

Thus, the author's CHDM theory incorporates the WFE mechanism as a very reasonable alternative to the standard ΛCDM cosmology theory that *non-baryonic* dark matter chilled first during the dark cosmic epoch (which immediately pre-ceded cosmic dawn) and then interacted with (i.e., chilled) primordial H I during cosmic dawn. The author's proposed WFE mechanism is a more simple and direct explanation. More importantly, it better explains the measured intensity and timing of the redshifted 21-cm signal at the beginning of cosmic dawn. The author proposes that it was the first *stars* which triggered the chilling of CMB-equilibrated H I, rather than exotic non-baryonic dark matter particles. To put it simply, it appears likely that *the 'cold dark matter' interacting with cosmic dawn CMB-equilibrated H I was, in fact, the first of the atomic hydrogen to be chilled by the Lyα radiation of the first stars.*

2.5 The hydrogen snow cloud model

For readers to become comfortable with the idea that cold hydrogen (molecular as well as atomic) could still be invisible and, therefore, missing from the baryonic budget, a brief description of Walker and Wardle's hydrogen snow cloud model [15] is in order. In their model, molecular hydrogen intermixed with small amounts of atomic hydrogen and helium can theoretically condense to a cold, high-density regime where solid or liquid hydrogen can form. By a complex mechanism, an inverted entropy gradient forms, allowing for the cloud outer layers to maintain an equilibrium state such that they are *below* the CMB temperature. Crucially, Walker and Wardle calculate specific model luminosities to be so low that such hydrogen snow clouds are, effectively, 'a type of baryonic dark matter' (their words). While the supercooled outer envelope of these snow clouds is mostly in the form of molecular hydrogen, Walker and Wardle presume there to be less cold H I in the snow cloud interiors. Therefore, effectively, the atomic and molecular hydrogen in these snow clouds is invisible to direct observation (i.e., dark). Moreover, there is, as of yet, no good reason why such hydrogen snow clouds could not be in large quantity within and around galaxies. This is CHDM in a somewhat different configuration, but dark hydrogen nonetheless.

2.6 The new galactic pin scintillation method for observing otherwise dark baryonic matter

In January of 2021, Wang et al. [16] reported first results of an ingenious method to observe otherwise invisible baryonic matter in the MW. By using the Australian Square Kilometer Array Pathfinder (ASKAP), they were able to track

radio scintillations of such matter by using distant galaxies as 'locator pins' to map their extent. A degrees-long filamentous cloud was observed. As described by Wang, 'This gas is undetectable using conventional methods, as it *emits no visible light of its own and is just too cold for detection via (usual) radio astronomy.*' Artem Tuntsov, another of the authors, suggested the possibility that their cloud could be a hydrogen snow cloud having undergone tidal disruption by a nearby star [17]. This is a new method which will undoubtedly be used to identify a great deal more MW hydrogen dark matter than has been possible to measure otherwise.

3. Discussion

Given the CHDM theory presented here, it is useful to consider a reasonable cosmic evolution scenario following the CMB emission epoch. We begin with the CMB anisotropy pattern created when the universe was transitioning from a 3,000 K plasma ball to a hot neutral gas of mostly atomic hydrogen.

The denser regions within the CMB anisotropy pattern presumably followed the positive feedback of gravity to become the galaxies, galaxy clusters, and filaments we observe. Meanwhile, the fractal distribution of less dense regions of the CMB anisotropy pattern intricately interlaced with the denser regions presumably became much less dense, owing to ongoing universal expansion and cooling. These cooler primordial hydrogen regions ultimately became the interstellar, circumgalactic, and intergalactic deep space we see today. To summarize, the denser regions of the CMB anisotropy pattern became warm to hot gas clouds and hot stars, while primordial hydrogen atoms of deep space became increasingly cold, following the descending CMB temperature.

During the early cosmic dawn this otherwise *invisible* atomic hydrogen became highly visible while it was decoupled from the CMB temperature by the Lyα UV radiation of the first stars. However, continuing cosmic expansion and cooling eventually brought the increasingly-separated primordial hydrogen atoms back into CMB equilibrium. Therefore, it appears likely that this mostly invisible primordial hydrogen is still present in deep space in great abundance. Its low kinetic energy, low average vacuum density, tiny scattering cross-section, and remoteness from light sources makes it the most difficult chemical species in the universe for us to locate and measure. One can certainly understand why, to this point, *indirect* observations, such as galactic rotation curves, have been necessary to provide support for the existence of dark matter.

A discussion of the cosmic evolution of primordial hydrogen would be incomplete without a specific focus on its role in galactic evolution and dynamics. By the end of the cosmic dark age, the universe, according to the widely-accepted big bang theory, was at a CMB radiation temperature of a little less than 100 K. The first stars of cosmic dawn had not yet ignited. In their place were rapidly-accumulating concentrations of warming primordial hydrogen interspersed with lesser amounts of primordial helium and lithium. Intimately interlaced with these gravitating and warming hydrogen clouds and 'pre-stars' were zones of hydrogen still equilibrated with the CMB temperature and destined to be, with further cosmic expansion, the cold atomic hydrogen of interstellar, circumgalactic, and intergalactic deep space. According to the CHDM theory, this was the slowly-cooling primordial hydrogen destined to be what we are currently calling 'cold dark matter.'

Not surprisingly, because deep space is interlaced between today's stars, galaxies, galaxy clusters and filaments, deep space primordial hydrogen undoubtedly has a gradient of concentrations and temperatures (i.e., velocities). This depends

upon its precise interstellar, circumgalactic or intergalactic location. Thus, the deep space interstellar and circumgalactic vacuum density averages approximately one atom per cubic centimeter, and the deep space intergalactic vacuum density averages approximately one atom per cubic meter. Presumably, in the vicinities of particularly dynamic and concentrated star formation, the interstellar primordial hydrogen is warmed up by energetic photons and concentrated stellar winds, to the point where it can become either visible or highly depleted within these zones. This mechanism may account for observations of a 'cored' (i.e., relatively depleted) dark matter, as hydrogen, distribution near the centers of active star-forming galaxies.

The study by Read et al. [18] of nearby dwarf galaxies showed that those which stopped forming stars more than 6 billion years ago tended to be cuspier than those with more recent 'bursty' star activity. The more recently-active galaxy centers tended to show more pronounced dark matter coring. The Read findings agree well with models where dark matter (baryonic or non-baryonic) is heated up and/or redistributed by concentrated active star formation. This interpretation fits nicely with the CHDM theory concerning the galactic evolution of primordial hydrogen. If this is the correct interpretation, then many bizarre properties of non-baryonic dark matter become unnecessary.

With the cosmic and galactic evolution scenario presented above, it should be apparent that the theorized non-baryonic dark matter is not required in order to understand the structural distribution of visible matter we see today. The opposing processes of gravitational clustering and cosmic expansion provided for a divergence of outcomes within the primordial hydrogen. Presumably, approximately one-sixth of this primordial matter gravitationally collapsed sufficiently to become the visible matter portion of our universe, and the remainder of this primordial matter became the CHDM of deep space.

As for predictions having to do with CHDM, the following appear to be likely:

3.1 Improved methodologies for detecting baryonic dark matter

There will be many more creative methodologies invented over the next decade which will indirectly locate and quantify otherwise invisible collections of cold hydrogen in the MW and its circumgalactic medium. Some of these methodologies may even be applicable to nearby galaxies.

3.2 Tightening constraints on dark matter

There will be tightening dark matter constraints around a particle m_x value of 0.938 GeV (i.e., the mass-energy of neutral atomic hydrogen).

3.3 Computer simulations of CHDM

Computer simulations of galaxy formation and evolution which incorporate the CHDM theory presented herein will show excellent correlations with observations, including the coring effect of heating and/or ejecting cold interstellar hydrogen from active galactic centers with bursty star formation.

3.4 No exotic non-baryonic dark matter

No exotic non-baryonic dark matter fitting the observed qualitative and quantitative dark matter constraints will ever be discovered.

4. Summary and conclusions

An explanation has been given as to why very low density, deep space, primordial atomic hydrogen in its lowest energy electron spin ground state should be largely invisible, especially when close to the CMB temperature. Calculations made on the 20 kpc radius Posti & Helmi halo sphere support this theory, especially when one realizes that an average halo vacuum density of only 0.77–1.0 hydrogen atom per cubic centimeter dwarfs the visible matter of the MW galactic disk and bulge.

Further support for the CHDM theory is provided by the EDGES study of the redshifted 21-cm H I line corresponding to cosmic dawn. The cosmic dawn dark matter constraints given in Barkana's review, and McGaugh's arguments for a 'purely baryonic universe,' fit nicely with the theory presented herein. The most reasonable mechanistic explanation for the intensity and timing of the cosmic dawn signal appears to be the Wouthuysen-Field effect. There appears to be no necessity for an exotic non-baryonic intermediary in the creation of this signal.

Exciting recent theoretical work on the hydrogen snow cloud model also provides some rationale for an abundance of extremely cold hydrogen invisible to direct observation. The new galactic pin scintillation method for indirect observation of 'baryonic dark matter' not reliant upon gravitational phenomena is also exciting. These new ideas and methods bode well for additional inventive studies over the ensuing decade.

The discussion section has focused on providing reasonable cosmic and galactic evolution scenarios for primordial atomic hydrogen which clearly do not require a *pre-existing* structural scaffold of non-baryonic dark matter. Primordial hydrogen created the structure we see. A reasonable CHDM explanation for a correlation between 'cored' galactic dark matter distribution and active galactic centers has also been given. This is consistent with observations reported by Read, et al.

Finally, several predictions having to do with CHDM have been made for the coming decade of observations and simulations.

In conclusion, it is worth asking the following question:

'If interstitial cold atomic hydrogen in its lower ground state is qualitatively and quantitatively sufficient to explain dark matter observations to date, do we really need to spend more of our time and money continuing to look for anything else?'

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