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How Cloud-9 Observations Could Be Consistent with the Cold Hydrogen Dark Matter (CHDM) Theory (a Brief Note)

Eugene Terry Tatum

Independent Researcher, Bowling Green, KY, USA
Email: ett@twc.com

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Abstract

It is suggested that the CHDM theory can be seamlessly integrated into the ΛCDM model and cosmological timeline, including a likely explanation of Cosmic Dawn and "Cloud-9" observations. Confirmatory evidence necessary for acceptance of the CHDM theory may lie in further study of the Cloud-9 dark matter halo or the halo of another RELHIC gas cloud, as described herein. For example, the discovery of an unusually strong 21-cm absorption line within a quasar spectrum in the background of a RELHIC would provide strong evidentiary support for CHDM. Counterarguments to the CHDM theory which focus on "missing" hydrogen baryonic matter appear to be refuted by comparing the Posti & Helmi 20 kpc radius Milky Way halo dark matter mass (635 billion solar masses) to a high-end estimate of the deep space cold neutral hydrogen mass (827 billion solar masses) within the same halo.

Keywords

Cloud-9, Dark Matter, Cold Hydrogen Dark Matter, CHDM, Cosmic Dawn, Circumgalactic Medium, RELHIC, Wouthuysen-Field Effect

1. Introduction and Background

Observations of "Cloud-9" [1] reveal it to be a non-rotating spherical cloud of dark matter and visible warm HI hydrogen gas. It is roughly 14 million light-years from the Milky Way galaxy and receding from us at the same velocity as its neighboring spiral galaxy, M94. Of note, Cloud-9 appears to be the best example to date of a Reionization-Limited HI Cloud (RELHIC) [2]. As predicted by the Lambda Cold Dark Matter (ΛCDM) model of cosmology, a RELHIC has the features of a "failed galaxy". As such, Cloud-9 appears to be starless, despite its spherical configuration, its dark matter halo of greater than one billion solar masses, and its visible HI gas of approximately one million solar masses.

There are important differences between a normal galaxy and the theoretical RELHIC. Galaxies spin and, by definition, have numerous stars which are the end result of gas cooling into gravitational collapse. The portions of the galactic cloud which become most dense by collapse become the hot ionized stars. A RELHIC, in contrast, gets stuck in a thermal equilibrium and does not have sufficient mass to cool further, collapse, spin, and form stars. Thus, as inferred from simulations, there is a critical mass threshold for the ΛCDM RELHIC, and Cloud-9 appears to be slightly below this threshold. Hence, it appears to be the current best example of a RELHIC type of failed galaxy.

The importance of finding and studying a RELHIC is that such an object is very likely to reveal clues about the fundamental nature of dark matter and its contribution to structure formation in the early universe. In the ΛCDM model, Cosmic Dawn was when the first stars formed in the universe. These are thought to have been giant blue stars emitting intense ultraviolet radiation, including Lyman-alpha radiation, with its characteristic effects on primordial hydrogen in the ground state. Simultaneously with the giant blue stars, the Cosmic Dawn HI hydrogen spin temperature was expected to have declined well below the temperature of the cosmic microwave background (CMB). In fact, a surprisingly large drop in Cosmic Dawn HI hydrogen spin temperature has now been observed [3]. According to the ΛCDM model, this decoupling of hydrogen temperature was presumed to be a result of cold dark matter interacting with and cooling primordial hydrogen into the familiar structure (galaxies and filaments, for example) of the early universe. It is believed that the Cloud-9 RELHIC, with further study, may reveal something about the fundamental nature of this dark matter and hydrogen interaction in the transition between the cosmic Dark Age and Cosmic Dawn.

1.1. The ΛCDM Timeline

The ΛCDM model of cosmology offers the following universal timeline: beginning with the CMB anisotropy map at about 379,000 years following the Big Bang, it is believed by most cosmologists, including the present author, that the areas of increased CMB density eventually collapsed, by gravitational attraction, to become the galaxies, galaxy clusters and filaments we currently see. At the same time, the lower density interstices of the CMB anisotropy map, following continued cosmic adiabatic expansion, cooled over billions of years into the interstellar and intergalactic deep space, including the voids. It is also believed that, between the "end of decoupling" and the formation of the first stars, the universe was completely dark. This is called the cosmic Dark Age. Yet, at the same time, sufficiently dense collections of dark matter and primordial hydrogen and helium were cooling and collapsing by gravitational attraction into denser structure eventually to heat up, re-ionize, and form the first stars of Cosmic Dawn at about 100 million years after the Big Bang. It is during Cosmic Dawn, according to the ΛCDM model, that the dark matter chilled the primordial hydrogen and decoupled its temperature from the CMB temperature. This period of hydrogen temperature decoupling from the CMB temperature is believed to have lasted from about 100 million to about 250 million years after the Big Bang. Thereafter, the slow-moving, low-density, deep space hydrogen re-equilibrated with the CMB temperature.

To summarize the above ΛCDM timeline scenario, there is believed to have been a cold dark matter of unknown nature which chilled and decoupled the primordial hydrogen from the CMB temperature during the period of re-ionization at Cosmic Dawn. The observed strong 21-cm signal and spin temperature at the nadir of temperature decline, about 170 million years after the Big Bang, is taken as evidence of this baryonic and dark matter (b-DM) interaction, bringing the two entities together in the process of structure formation.

1.2. The CHDM Theory

In 2019, this author was invited to a dark matter workshop at the World Science Festival. There he had the opportunity to present to colleagues his theory concerning the possible cold hydrogen nature of dark matter. Following this workshop in May of 2019, his first paper describing the rudiments of this theory was published in a peer-reviewed scientific journal [4]. As supportive observational studies accumulated, he published additional peer-reviewed papers on the theory, eventually simplified in name to "Cold Hydrogen Dark Matter" (CHDM) [5] [6].

According to this theory, CHDM is a *species and condition* (both are necessary) of cold neutral hydrogen in its lower ground state, specifically that which has its electron in the anti-parallel spin state. Because the hydrogen electron in this ground state has no possible lower energy state, it *cannot* emit light under any known circumstances. Furthermore, the CHDM condition has very specific features which make it mostly invisible to direct observation. For this species of ground state hydrogen to act as dark matter, it must be slow-moving (*i.e.*, "cold"), its density must average no more than about one atom per cubic centimeter, and its location must be in deep interstellar or intergalactic space. Thus, collisions with neighboring atoms and absorptions of photons are rare events. The only other exceptions to its near-complete invisibility appear to be its gravitational influence, including capacity for gravitational lensing, and its *signature* ultrafine 21-cm *absorption* line visible in lines of sight to distant background stars and quasars. The importance of the latter feature (21-cm absorption line) will be described next.

The flipping of the spin state of hydrogen in its ground state results in the emission or absorption of a 21-cm photon. For example, the spin flip transition of HI hydrogen with parallel electron spin results in 21-cm photon *emission*, and the spin flip transition of ground state hydrogen with anti-parallel electron spin *requires* 21-cm photon *absorption*. Therefore, according to the CHDM theory, wherever radio telescope astronomers observe 21-cm emissions, they are observing locations where HI hydrogen atoms are flipping to the lower-energy (anti-parallel) electron ground state and *creating* CHDM, if the temperature, density and location conditions mentioned above are also met. And wherever astronomers are observing the hyperfine 21-cm absorption line within lines of sight to distant stars and quasars, they are observing 21-cm photon absorption by CHDM atoms, if the temperature, density and location conditions mentioned above are also met. Furthermore, decades of such line-of-sight observations have established that these atoms of deep interstellar and intergalactic space are at an average density of approximately one atom per cubic *centimeter* (deep interstellar and proximate halo) and one atom per cubic *meter* (deep intergalactic) [7]-[9].

2. Discussion

The author agrees that the above ΛCDM timeline description is a plausible scenario, and that CHDM theory can be seamlessly integrated into this scenario in the following way. Let us first assume that, by the end of the cosmic Dark Age, the primordial hydrogen consistent with CHDM was mostly in the low-density interstices within and between the gravitating clouds of hydrogen which would become stars and galaxies. Let us further assume that the first stars of Cosmic Dawn within these hydrogen clouds were giant blue stars emitting high intensity ultraviolet radiation, including Lyman-alpha radiation. If these two plausible assumptions hold, the following sequence appears likely:

The Lyman-alpha radiation from the first stars, over the first tens of millions of years of Cosmic Dawn may have transitioned much of the primordial HI hydrogen from its parallel electron spin ground state to its lower-energy, anti-parallel, electron spin ground state. This would likely have happened due to the well-known Wouthuysen-Field coupling effect [10]-[12], whereby, as a result, intense 21-cm emissions would emanate from the hydrogen gas in the vicinity of the giant blue stars. Thus, during Cosmic Dawn, there would be an observable strong baryonic 21-cm signal and a pronounced decoupling of the hydrogen atom spin temperature from the CMB temperature (a process known as "CMB decoupling"). Similar Cosmic Dawn observations consistent with Wouthuysen-Field coupling effects have recently been made [3] and have been interpreted by McGaugh [13] as evidence of a "purely baryonic universe". By this, McGaugh is presumably saying that only baryonic interactions are needed for such EDGES study observations, as opposed to requiring some as-yet mysterious non-baryonic dark matter to attract and interact with the primordial hydrogen. McGaugh has made some excellent arguments in this regard, which appear to be consistent with CHDM theory and appear to disfavor any requirement for baryonic matter interactions with non-baryonic dark matter (b-DM) to explain the pronounced CMB decoupling. The present author is not aware of any reliable quantitative modeling studies to support or refute a specific ratio of the two ground state hydrogen species during Cosmic Dawn. This is for future simulation studies modeling CHDM.

2.1. The Potential Relevance of Cloud-9

This leads us to a brief discussion as to how the observations of Cloud-9 might be consistent with the CHDM theory. According to the above CHDM scenario, presumably the giant blue stars of Cosmic Dawn would delineate two species of ground state hydrogen: abundant and very cold CHDM atoms below the CMB temperature because of Lyman-alpha radiation bombardment and spin flip transition; and a significantly smaller population of visible HI hydrogen at or above the CMB temperature.

The features observed in Cloud-9 appear to fit well for a RELHIC hydrogen cloud which has a mass just under the threshold for further gravitational collapse and star formation. Furthermore, Cloud-9 appears to be almost entirely composed of dark matter, possibly amounting to as much as five billion solar masses in comparison to about one million solar masses of ordinary visible hydrogen. So, the ratio of dark matter to visible matter in this cloud might be as much as 5000 atoms of dark matter for every atom of visible matter. Thus, in Cloud-9, we see a nearly pure and roughly spherical collection of dark matter which can be subjected to numerous future observational studies to elucidate its fundamental nature.

In the context of the CHDM theory integrated with the ΛCDM scenario mentioned above, Cloud-9 appears to be a failed galaxy from the Cosmic Dawn epoch, wherein much of the primordial hydrogen has been bombarded by ultraviolet radiation and converted to CHDM. So, one wonders if this nearly pure cloud of dark matter is mostly hydrogen in its lower ground state (with anti-parallel electron spin), with a small admixture of warm visible hydrogen and primordial helium. We eagerly await the results of further observational studies to further determine its composition. Such additional studies might include a search for quasars in the background of the dark matter halo portion of Cloud-9. Such a finding might allow for spectral analysis of the quasar light shining through Cloud-9 to further delineate its composition, and possibly to support or refute an abundance of CHDM features in the dark matter. For example, a strong 21-cm absorption signal in a quasar spectrum within the dark matter halo would appear to support the CHDM theory. In terms of the presumed prior history of Cloud-9, the finding of only hydrogen and helium would further support a primordial nature of the cloud. Something in the spectral analysis might also give us further clues as to what is or is not ruled out with respect to the nature of dark matter. Any evidence of ionization from the cosmic ultraviolet background might point to additional compositional details otherwise hidden in the absence of spectroscopic analysis. Additional studies may also tighten the constraints on whether there was a prior star-formation history within Cloud-9, the absence of which would further support its likely RELHIC nature.

2.2. The Likely Underestimation of the Halo Mass of Cold Neutral Hydrogen in Its Lower Ground State

Finally, it is useful here to address a counterargument often made with respect to the CHDM theory. It is frequently claimed that observational studies of neutral hydrogen absorption lines indicate that such ground state neutral hydrogen does not contain enough mass to explain the dark matter problem. Indeed, astronomers struggle to explain where all the "missing baryons" are, even with respect to the current ΛCDM model [14]. And yet, as detailed in this author's previous "Dark Matter as Cold Atomic Hydrogen in its Lower Ground State" publication [5], the Posti & Helmi study [15] indicated the presence of about 635 billion solar masses of dark matter within a 20 kpc (65.2 thousand light-year) radius halo sphere centered on the Milky Way disk. This is mostly the "inner core" (*i.e.*, proximate to the disk) of a much larger one million light-year radius halo, the Milky Way "corona". As a check by this author on the Posti & Helmi dark matter mass number, an estimate of approximately one atom of cold lower ground state hydrogen (on *average*) per cubic centimeter of interstellar space within the inner core was used to calculate that the CHDM within the Posti & Helmi 20 kpc radius halo sphere could amount to as much as 1.645×10^{42} kg equaling 827 billion solar masses! While it is understood that the average hydrogen density is acutely dependent upon the radial distance from the galactic plane, this average density of mostly invisible cold hydrogen does not appear to be beyond the realm of possibility. Recent studies [16] [17] of hydrogen within the inner core of the Milky Way halo have emphasized the biases inherent in estimating the gas densities of different hydrogen species within the circumgalactic medium (CGM). Zheng *et al.*, for example, state "observations of the Milky Way's CGM, especially those using HI 21-cm and QSO absorption lines, are highly biased". This is *especially* true for the cold hydrogen gas component. French *et al.*, for example, state, "…this approach is inherently imprecise, as it relies on the assumption that halo gas exists exclusively at high velocity. Simulations show that a large fraction of halo gas may be hidden at low velocity, where it blends with the disk." Thus, the Navarro-Frenk-White (NFW) profile density distribution numbers pertaining to the halo inner core cannot be considered the last word on the actual halo density of cold HI gas. Furthermore, with respect to the 20 kpc radius sphere mentioned above, even if one only assumes 0.75 atom of cold neutral hydrogen on average in the lower ground state per cubic centimeter, this will match the Posti & Helmi dark matter mass given above. So, to give but one example based upon careful observation, the amount of CHDM in the 20 kpc radius halo sphere centered on the Milky Way disk could potentially be greater than the visible matter in the disk itself! This is not an unreasonable high-end estimate, based upon Posti & Helmi's observations and potentially achievable *average* halo inner core cold hydrogen densities, and would appear to suggest that the overall halo mass of neutral hydrogen in its lower ground state could well be severely *underestimated* at the present time.

3. Alternative Hypotheses for the Cloud-9 Observations

Given that the RELHIC hypothesis was partially based on hydrodynamic simulations, and the fact that there is obviously some turbulence of matter within the interstellar and circumgalactic mediums, one should at least consider Batista & Pace's argument [18] that hydrodynamic models using Navier-Stokes equations can also simulate flatness of galactic rotation without necessarily requiring a dark matter hypothesis. However, the finding of a strong 21-cm absorption signal within a quasar spectrum passing through a RELHIC such as Cloud-9 would be discriminating and give much stronger support to the CHDM theory. Obviously, since there is still much to be learned about halo constituents and the exact composition of Cloud-9 and other future RELHICs, one can neither confirm nor refute the CHDM theory at the present time.

4. Summary and Conclusion

It has been suggested that the CHDM theory can be seamlessly integrated into the ΛCDM model and cosmological timeline, including a likely explanation of Cosmic Dawn and "Cloud-9" observations. All that would appear to be required for this to happen would be to understand and accept McGaugh's powerful arguments that the EDGES study observations of Cosmic Dawn are in favor of a "purely baryonic universe". Thus, the baryonic dark matter at Cosmic Dawn which was likely responsible for the surprisingly large CMB temperature decoupling seen in the HI hydrogen spin temperature was cold neutral hydrogen in its lower ground state. Confirmatory evidence necessary for acceptance of the CHDM theory may lie in further study of the Cloud-9 dark matter halo or the halo of another RELHIC gas cloud, as described herein. For example, the discovery of an unusually strong 21-cm absorption line within a quasar spectrum in the background of a RELHIC would provide strong evidentiary support for CHDM. Counterarguments to the CHDM theory which focus on "missing" hydrogen baryonic matter appear to be refuted by comparing the Posti & Helmi 20 kpc radius Milky Way halo dark matter mass (635 billion solar masses) to a high-end estimate of the deep space cold neutral hydrogen mass (827 billion solar masses) within the same halo. See again [5]. Obviously, since there is still much to be learned about the colder halo constituents and the exact composition of Cloud-9 and other future RELHICs, one can neither confirm nor refute the CHDM theory at the present time. Presumably, future observations will help to settle the matter.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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