Natural Explanation for 21 cm Absorption Signals via Axion-Induced Cooling

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The EDGES Collaboration has reported an anomalously strong 21 cm absorption feature corresponding to the era of first star formation, which may indirectly betray the influence of dark matter during this epoch. We demonstrate that, by virtue of the ability to mediate cooling processes while in the condensed phase, a small amount of axion dark matter can explain these observations within the context of standard models of axions and axionlike particles. The EDGES best-fit result favors an axionlike particle mass in the (10, 450) meV range, which can be compressed for the QCD axion to (100, 450) meV in the absence of fine tuning. Future experiments and large scale surveys, particularly the International Axion Observatory (IAXO) and EUCLID, should have the capability to directly test this scenario.

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Introduction.—After recombination, between the thermal decoupling of baryons and the cosmic microwave background (CMB) and the era of first star formation, the Universe entered a prolonged period of cooling known as the dark ages. Intriguingly, this epoch is both largely untested by observations, and in the standard Λ CDM cosmology, relatively predictable and easily understood. As such, it can serve as a precise probe of physics outside of the Λ CDM paradigm.

One key observable is related to the absorption of 21 cm light at that time, arising from the neutral hydrogen present filtering background radiation, and thereby imprinting a characteristic spectral distortion on wavelengths close to atomic transitions. This feature redshifts to the 80 MHz range today, and has been recently observed by the Experiment to Detect the Global Epoch of Reionization Signature (EDGES) Collaboration.

Their result is an anomalously strong 21 cm absorption feature from $z \in (20, 15)$, corresponding to the era of first star formation [1]. The amplitude of this signal is

$$T_{21} \simeq 35 \text{ mK} \left(1 - \frac{T_\gamma}{T_s} \right) \sqrt{\frac{1+z}{18}} \simeq -0.5^{+0.2}_{-0.5} \text{ K}, \quad (1)$$

where T_γ is the CMB temperature, T_s the singlet/triplet spin temperature of the hydrogen gas present at that time, and the

uncertainties quoted are at 99% confidence level. Once stellar emission of UV radiation begins at $z \sim 20$ we expect that $T_\gamma \gg T_s \gtrsim T_{\text{gas}}$, due to the decoupling of the CMB and hydrogen gas at $z \sim 200$, and the coupling of the spin temperature to the kinetic gas temperature. In the standard Λ CDM scenario $T_\gamma|_{z \sim 17} \simeq 49 \text{ K}$ and $T_{\text{gas}}|_{z \sim 17} \simeq 6.8 \text{ K}$, so we expect $T_{21} \gtrsim -0.2 \text{ K}$. The resulting significance of this deviation from the Λ CDM prediction is estimated to be 3.8σ .

One approach to resolving this discrepancy relies upon interactions with cold dark matter (CDM) to lower the gas temperature. However, as demonstrated in Ref. [2], the interaction cross section required to achieve this is prohibitive for models of dark matter. Consistency with other experimental and observational constraints ultimately limits models capable of explaining the EDGES observation to being comprised of just 0.3%–2% millicharged dark matter, with masses and millicharges in the (10,80) MeV and (10^{-4} , 10^{-6}) ranges, respectively [3–5]. A number of other approaches have also been explored, including adding additional dark sector interactions, modifying the thermal history, and injecting additional soft photons during that epoch [6–10]. Several axion-theoretic explanations have also been recently proposed [11–13], but we emphasise for clarity that our approach differs in many essential respects from these.

More specifically, in the following we propose a dark-matter theoretic approach, which relies upon the speculated ability of axion dark matter to form a Bose-Einstein condensate (BEC) [14,15]. While behaving in many respects as ordinary CDM, a particularly interesting aspect of this phenomenon exists in the ability of this condensed

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state to induce transitions between momentum states of coupled particle species and thereby mediate cooling processes. This scenario was originally invoked in Ref. [16] to lower the photon temperature in the era of big bang nucleosynthesis (BBN), in order to adjust the baryon-to-photon ratio and thus ease the discrepancy between the observed and predicted primordial ^7Li abundance.

As we will see in the following, by analogously lowering the hydrogen temperature prior to the cosmic dawn this mechanism can explain the EDGES observations in the context of axion and axionlike particle (ALP) models. The implied parameter range is close to existing experimental limits, and so could be tested at the next generation of axion experiments and via large scale surveys, particularly IAXO and EUCLID, respectively [17,18].

Axion dark matter condensation.—The underlying conditions for BEC formation are that a system comprise a large number of identical bosons, conserved in number, which are sufficiently degenerate and in thermal equilibrium [19]. As such, the formation of a BEC of CDM axions seems a reasonable possibility.

Nonetheless, there has been some controversy in the literature around this and the value of the resulting correlation length [20–23]. In particular, it was ultimately concluded in Ref. [23] that although a Bose-Einstein condensate can form, the claim of long-range correlation in the case of attractive interactions is unjustified. It has, however, been argued more recently that these findings may be overly reliant on the criterion of homogeneity, while a BEC can be inhomogeneous and nonetheless correlated over its whole extent, which can be arbitrarily large [19]. Addressing these points is somewhat beyond the scope of this Letter, and so we instead proceed under the assumption that the BEC cooling mechanism functions as advertised in Ref. [14].

It is nonetheless key to note that for generic ALPs with repulsive self-interactions, the thermalization rate is

$$\Gamma_a/H \sim \lambda n_a m_a^{-2}/H, \quad (2)$$

where λ , n_a and m_a are, respectively, the quartic coupling, and the cold axion number density and mass. Since this increases with time, long range order will eventually be established and condensation can be reasonably and uncontroversially expected [23].

For the QCD axion, which provides both a compelling solution to the strong CP problem and a particularly attractive target for beyond the standard model physics searches [24–30], all available interactions are, however, attractive. The thermalization rate due to gravitational interactions is given by

$$\Gamma_a/H \sim 4\pi G n_a m_a^2 l_a^2/H, \quad (3)$$

where G is Newton's constant, and l_a is the correlation length [14]. This scales as t/a , where a is the scale factor,

and so by the logic of Ref. [19] can also be relied upon to ensure long-range order and the condensed phase persists.

Once formed, the large-scale gravitational field of the condensate can reduce the momenta of particle species, with the cooling effects beginning once the characteristic relaxation timescale Γ exceeds the Hubble rate, so that

$$\Gamma/H \sim 4\pi G m_a n_a l_a \omega / \Delta p H \gtrsim 1, \quad (4)$$

where ω and Δp are the energy and momentum dispersion of the particle species in question.

This phenomenon offers the possibility to then explain the anomalous EDGES result, with condensed axion dark matter cooling the primordial hydrogen after it decouples from the CMB at $z \sim 200$. This latter point is essential, as if axion cooling begins while the CMB and hydrogen remain in thermal equilibrium, the effect on Eq. (1) will be negligible. Of course the onset of cooling must also be prior to the cosmic dawn, and the effect in total must give the correct EDGES absorption magnitude. As we will see in the following, and perhaps surprisingly, these various requirements can be simultaneously accommodated by an ALP which may or may not also function as the QCD axion. In practice the EDGES observation uniquely selects a small range for m_a , which is compatible with present-day axion phenomenology and can conceivably be explored at the next generation of axion experiments.

Condensate-induced hydrogen cooling.—Using the formulae of the previous section, our starting point is the baryon cooling rate at the time of matter-radiation equality,

$$\left. \frac{\Gamma_H}{H} \right|_{t_{\text{eq}}} \sim \sqrt{\frac{3m_H}{16T_{\text{eq}}}} \frac{\Omega_a h^2}{\Omega_{\text{DM}} h^2}, \quad (5)$$

where $\Omega_a h^2 / \Omega_{\text{DM}} h^2$ is the fraction of the cooling-induced ALP density over the dark matter relic density, where we have used the Friedmann equation at this time to identify $3H^2 \simeq 16\pi G \rho_{\text{DM}}$, neglecting the contributions of visible matter and dark energy, and, assuming that we are in the condensed phase, identified $l_a \sim 1/H$. By virtue of the Maxwell-Boltzmann distribution $\Delta p \simeq \sqrt{3m_H T_H}$, and at this temperature we can identify $\omega \sim m_H$.

As $m_H \gg T_{\text{eq}}$ we evidently need a small ($\Omega_a / \Omega_{\text{DM}}$) ratio to ensure cooling only begins when $z \in (200, 20)$. To be more precise we can note that since $a \propto t^{2/3}$ during matter domination, $\Gamma_H/H \propto 1/\sqrt{T}$. This then implies that after matter-radiation equality,

$$\frac{\Gamma_H}{H} = \frac{\Gamma_H}{H} \bigg|_{t_{\text{eq}}} \left(\frac{T_{\text{eq}}}{T_H} \right)^{1/2}. \quad (6)$$

Since $T_{\text{eq}} \sim 0.75 \text{ eV} \simeq 8.7 \times 10^3 \text{ K}$, and we require axion-induced cooling to occur between $T_H^{z=200} \sim 475 \text{ K}$ and $T_H^{z=20} \sim 10 \text{ K}$, we can first establish that we require

$$\Omega_a h^2 / \Omega_{\text{DM}} h^2 \in (0.22, 1.5) \times 10^{-5}. \quad (7)$$

It is important to note that once the BEC forms, we will have two distinct populations of cold axions; those that are in the condensed state, and a remnant thermal population. Hydrogen can in principle interact with both; however, there exists a key distinction: scattering from the cold thermal axions will simply raise their temperature, while scattering from the condensed axions will typically liberate them from the BEC, given the energies involved, and into the thermal population. However, in Ref. [22] the rate at which the BEC occupation number can change by scattering with external particles is calculated, finding that the latter number-changing process should be vanishingly rare. Energy conservation then dictates that

$$\rho_H(T_i) \simeq \rho_H(T_f) + \rho_a(T_f), \quad (8)$$

since the energy lost from the hydrogen must be transferred to the thermal axions. (For our parameter range of interest, photon cooling can be neglected. As n_H remains constant during axion cooling, to explain Eq. (1) we require $\rho_H(T_i)/\rho_H(T_f) \sim \mathcal{O}(1)$, implying ρ_H and ρ_a must be of the same order. Since $\rho_\gamma \gg \rho_H$, from the known baryon-photon ratio, the resulting ρ_a is too small to affect ρ_γ and hence T_γ . Thermal axion heating by photons is also strongly suppressed, as there is no large $\sqrt{m_H/T}$ factor in the corresponding equivalent of Eq. (5). We also note the principal constraint in the axion-induced cooling ${}^7\text{Li}$ scenario was a large resulting N_{eff} at recombination. For us this is not a cause for concern as we are operating at a much later epoch, and the thermal axions excited will be nonrelativistic.) In the case of cold hydrogen gas $\rho_H \simeq n_H(m_H + 3T/2)$ to lowest order, where n_H is the relic abundance. Since hydrogen comprises the majority of baryonic matter at this epoch we can use the baryon-to-photon ratio to estimate $n_H \simeq 6 \times 10^{-10} n_\gamma$, where $n_\gamma = 2\zeta(3)T_\gamma^3/\pi^2$ is the photon number density. Inserting a Maxwell-Boltzmann distribution for the thermal axions we have

$$\rho_a = \frac{T^4}{2\pi^2} \int_0^\infty \frac{\xi^2 \sqrt{\xi^2 + (m_a/T)^2}}{\exp(\sqrt{\xi^2 + (m_a/T)^2}) - 1} d\xi, \quad (9)$$

and we can solve Eq. (8) numerically for the cooling ratio T_i/T_f .

Assuming for simplicity that the change in z is negligible during the cooling process, we have

$$T_H^{z=17} \simeq T_H^{z=200} \left(\frac{z_c + 1}{200 + 1} \right)^2 \left(\frac{T_f}{T_i} \right) \left(\frac{17 + 1}{z_c + 1} \right)^2, \quad (10)$$

where z_c is the redshift at which cooling begins. Since dependence on this quantity cancels, we find

$$T_{21} = 35 \text{ mK} \left(1 - \frac{T_i}{T_f} \frac{T_\gamma}{T_H} \right) \sqrt{\frac{1+z}{18}}, \quad (11)$$

where T_γ and T_H take their usual ΛCDM values. In practice additional care is needed since basic redshift relations do not accurately capture the evolution of T_H in this region, so we use RECFAST to compute T_H and T_γ [31]. However, the resulting dependence in Eq. (11) is nonetheless correct, and so we can use Eq. (8) to find the resulting 21 cm absorption feature. This is given in Fig. 1, where we see the EDGES best-fit value favors an ALP with mass $m_a \in (10, 450) \text{ meV}$.

Since in the generic ALP case the relation between $\Omega_a h^2$ and m_a is unfixed, we cannot directly connect them to coupling constraints and thus standard axion phenomenology. However, for the QCD axion the corresponding f_a is given via

$$\Omega_a h^2 = 0.15 X \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6}, \quad (12)$$

where for Peccei-Quinn (PQ) symmetry breaking before inflation, $X \sim \sin^2 \theta_{\text{mis}}/2$, while for PQ symmetry breaking after inflation $X \in (2, 10)$ depending on the relative contributions of topological defect decays and vacuum misalignment [15]. This yields $f_a \in (1.2, 6.1) \times X^{-6/7} \times 10^7 \text{ GeV}$, which is in turn related through chiral perturbation theory to m_a via

FIG. 1. The ALP ($m_a, \Omega_a h^2$) space satisfying Eq. (7), color-coded with the resulting 21 cm brightness temperature at $z = 17$. Comparison with the best-fit EDGES result then suggests a $m_a \in (10, 450) \text{ meV}$ range of compatibility. Since the QCD axion fixes the relationship between these quantities in terms of the dark matter density parameter X appearing in Eq. (12), we overlay lines of fixed X to show the dependence on this quantity.

$$m_a \simeq 6 \text{ eV} \left(\frac{10^6 \text{ GeV}}{f_a} \right), \quad (13)$$

yielding $m_a \in (0.1, 0.5) \times X^{6/7} \text{ eV}$.

Note however that m_a is not freely varied in this case; each value is associated to a specific $\Omega_a h^2$, and thus the specific z and T_H at which cooling begins. Taking care to accommodate this, we find a one-to-one mapping between m_a and T_{21} . We also note for clarity that in this mass range we can expect both hot and cold axion dark matter, due, for example, to thermal production and vacuum misalignment, respectively.

This being the case, we also represent the QCD axion in Fig. 1 via lines of constant $X^{6/7}$. Since $X \in (2, 10)$ for PQ symmetry breaking after inflation, the minimum value for this quantity is realized for pre-inflationary symmetry breaking. In this case we have $X^{6/7} \sim 0.5$ in the absence of fine-tuning, assuming the initial misalignment angle is randomly drawn from a uniform distribution on $[-\pi, \pi]$, giving $\langle \theta_{\text{mis}}^2 \rangle = \pi^2/3$.

Varying X we find a preferred natural range of $m_a \in (100, 450) \text{ meV}$ for the QCD axion by virtue of the EDGES best-fit result, where each value gives $T_{21} \simeq -0.5 \text{ K}$ at $z \sim 17$ by solution of Eq. (8). Fixing $X = 1$ as a benchmark case we find $T_{21} \in (-1.75, -0.21) \text{ K}$ at $z \sim 17$, where we remind the reader that $T_{21} \simeq -0.21 \text{ K}$ is the standard ΛCDM result, which we reach in the limit of this mechanism being inoperative. Working backwards, the 99% confidence limits presented in Eq. (1) then in this case imply the range $m_a \in (120, 180) \text{ meV}$, with the best fit value corresponding to $m_a \simeq 150 \text{ meV}$.

QCD axion constraints.—Since the ALP case does not immediately translate to ordinary axion constraints, we can specialize to the QCD axion to gain some phenomenological insight and delineate the parameter values implied by the EDGES observation in this scenario, along with the various experimental and observational constraints which may apply. In Fig. 2 we reproduce constraints on the axion parameter space in our region of interest from Eq. [32], colour coded with the resultant value of T_{21} at $z = 17$ for the benchmark case of $X = 1$. As can be seen, the EDGES observations can be straightforwardly accommodated within the ordinary QCD axion band. Furthermore, much of the resulting preferred parameter space will be covered by the IAXO experiment, allowing the possibility of a direct confirmation of these findings.

We can also note from Ref. [33] that although our mass range of interest evades hot dark matter constraints at present, future large scale surveys such as the EUCLID mission are in conjunction with Planck CMB data projected to probe $m_a \gtrsim 150 \text{ meV}$ for the QCD axion at high significance, allowing this scenario to be definitively tested in the near future [34].

It is of course important to note that the full possible mass range favored by these results is for DFSZ-type

FIG. 2. The portion of the axion parameter space relevant for our purposes, reproduced from Ref. [32], with the 21 cm brightness temperature at $z \sim 17$ overlaid from axion-induced cooling processes in the benchmark case of $X = 1$. The yellow band denotes QCD axion models with varying electromagnetic or color anomaly coefficients, while the black curves indicate possible sensitivities for the proposed IAXO experiment. The best fit axion mass value preferred by the EDGES observations in this case is 150 meV, while beyond $\sim 300 \text{ meV}$ the ordinary ΛCDM result for T_{21} prevails. Variations in X enlarge the preferred range to $m_a \in (100, 450) \text{ meV}$ in the absence of fine-tuning, effectively shifting the color-coded region within the QCD axion band.

axions strongly disfavored due to stellar energy-loss arguments [29,30,32]. As such we are implicitly considering KSVZ-type models [27,28], although the ratio E/N of the electromagnetic to color anomaly is, however, allowed to vary within the usual range to accommodate variant models of the QCD axion [35,36].

Strictly speaking even then there is tension between our preferred mass range and the observed burst duration of SN 1987A, which favors $f_a \gtrsim 4 \times 10^8 \text{ GeV}$ for standard QCD axions [37]. This arises from an inference of the supernova cooling timescale, and thus energy loss to axions, from the time interval between the first and last neutrino observation. However, given that these limits are derived from a single observation, and not to mention our limited knowledge available about axion emission in this extreme environment (the resulting exclusion being “fraught with uncertainties” in the words of Ref. [37]), we can follow the example of others (e.g., Ref. [33]) and exercise a measure of caution in applying this constraint.

So-called “astrophobic” axion models are also of note here, where $\mathcal{O}(100) \text{ meV}$ axion masses are allowed at the cost of introducing some flavor-violating couplings [38,39]. Furthermore, we can also recapitulate at this point that ultimately the axion cooling mechanism leveraged here is gravitationally mediated, and so could be achieved with

no standard model couplings whatsoever, and thus no issues in this regard. By extension, the use of the QCD axion is in this context nonessential, and our primary results for generic axionlike particles can still apply nonetheless.

Discussion and conclusions.—The EDGES Collaboration has recently presented an anomalously strong 21 cm absorption profile, which may be the result of dark matter interactions around the time of the cosmic dawn. Despite a flurry of interest there is as of yet no clear consensus on the provenance of this effect, and indeed whether it is a signature of dark matter at all; however, these results nonetheless provide an exciting first window into a previously unexplored epoch.

We have in this Letter explored the potential of condensed-phase axion dark matter, previously employed in the service of photon cooling, to explain these anomalous observations via reduction of the hydrogen spin temperature during this epoch. By fixing the axion CDM relic density so that cooling begins within the appropriate epoch, we find that the resulting cooling effects are both capable of explaining the EDGES observations and compatible with present day axion phenomenology.

More specifically, we find that the EDGES best-fit result of $T_{21} \simeq -0.5$ K and the requirement that hydrogen cooling occur when $z \in (200, 20)$ are consistent with the cooling induced by an axionlike particle of mass $m_a \in (10, 450)$ meV. Specializing further to the QCD axion case, we find a preferred range $m_a \in (100, 450)$ meV, in the absence of fine-tuning.

Furthermore, future experiments and large scale surveys such as IAXO and EUCLID should have the capability to directly probe the relevant parameter region and thereby test this scenario. Indeed, as a dedicated direct-detection experiment sensitive in this mass range, IAXO offers particular promise with regards to this scenario. That said, as the underlying cooling mechanism relies only upon gravitational couplings it is not limited strictly to the context of models of the QCD axion, and so can also be arranged to occur in the primary scenario of axionlike particles with no standard model couplings whatsoever, which could then evade these bounds.

We also note Ref. [40], which appeared shortly after this Letter appeared online and deals with exactly the same scenario of axion BEC-induced cooling and 21 cm cosmology. A key point raised therein, which we have not previously addressed, is that this mechanism may have a damping effect on baryon acoustic oscillations (BAO). Although it is ultimately argued there that the net effect on BAO should be consistent with observations, it may be worthwhile to more deeply explore the consequences of this scenario for this and other cosmological observables.

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