First Star Formation in the Presence of Primordial Magnetic Fields

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Abstract

It has been recently claimed that primordial magnetic fields could relieve the cosmological Hubble tension. Fields of sufficient strength to relieve this tension would result in a magnetic field whose Alfvén velocity, \( v_a \), is comparable to the speed of sound, \( c_s \), at the start of structure formation. We consider the impact of such fields on the formation of the first cosmological objects, minihalos (\(<10^6 M_\odot\)), forming stars with zoom-in cosmological simulations tracking a single such minihalo. We seed each simulation with present-day field strengths of \( 2 \times 10^{-12} - 2 \times 10^{-10} \text{G} \) corresponding to initial ratios of Alfvén velocity to the speed of sound of \( v_a/c_s \approx 0.03-3 \). We find that when \( v_a/c_s < 1 \), the effects are modest. However, when \( v_a/c_s \approx 1 \), the starting time of the gravitational collapse is delayed and the duration extended as much as by \( \Delta \tau = 2.5 \) in redshift. When \( v_a > c_s \), the collapse is completely suppressed and the minihalos continue to grow and are unlikely to collapse until reaching the atomic cooling limit. Employing current observational limits on primordial magnetic fields we conclude that inflationary-produced primordial magnetic fields could have a significant impact on first star formation.

Unified Astronomy Thesaurus concepts: Primordial magnetic fields (1294); Population III stars (1285); Magnetic fields (994); Star formation (1569); Magnetohydrodynamical simulations (1966)

1. Introduction

Magnetic fields are observed throughout the local universe, in galaxies, in clusters of galaxies, as well as very possibly in the extragalactic medium. Observations of TeV blazars (Neronov & Vovk 2010) are most easily explained by the existence of an almost volume filling magnetic field permeating the space between galaxies. Recently it has also been shown by Jedamzik & Pogosian (2020) that magnetic fields of \( \sim 0.05 \text{nG} \) existant before the epoch of recombination show good promise to alleviate the 4\( \sigma \)-5\( \sigma \) cosmic Hubble tension and the \( \sim 2\sigma \) cosmic \( s_8 \) tension within standard Lambda cold dark matter (\( \Lambda \text{CDM} \)). The Hubble tension is the mismatch between the inferred small present-day Hubble constant \( H_0 \) from observations of the cosmic microwave background radiation by the Planck satellite when assuming \( \Lambda \text{CDM} \) (Planck Collaboration et al. 2018), and a larger \( H_0 \) inferred by local observations (Reid et al. 2019; Wong et al. 2019; Pesce et al. 2020). The \( s_8 \) tension is the difference between the \( \Lambda \text{CDM} \) predicted current matter fluctuation amplitude on a scale of 8 Mpc \( h^{-1} \) and that observed directly via weak lensing (Abbott et al. 2018; Asgari et al. 2020). It has been shown that weak magnetic fields induce density fluctuations on small, sub- Jeans comoving \( \sim \text{kiloparsec} \) scales before recombination (Jedamzik & Abel 2013) that would indeed alter the prediction for \( H_0 \) and \( s_8 \) within \( \Lambda \text{CDM} \) in a favorable way. Such fields necessarily would be of primordial origin.

There are two conceptually different possibilities for the generation of primordial magnetic fields (PMFs), magnetogenesis during inflation and post-inflationary generation (often referred to as “causal” scenarios) as for example during a first-order electroweak phase transition. Though multiple proposals exist (see Durrer & Neronov 2013; Subramanian 2016; Vachaspati 2020 for reviews), there is no preferred candidate. Inflationary scenarios have to lead to an approximate scale-invariant magnetic spectrum to be successful, whereas most causal scenarios develop a very blue Batchelor spectrum, with most magnetic power on small scales (Durrer & Caprini 2003; Saveliev et al. 2012). Stringent upper limits on PMFs from observations of the cosmic microwave background (CMB) radiation have been placed by Jedamzik & Saveliev (2019) at \( \lesssim 10^{-10} \text{G} \) and \( \lesssim 2 \times 10^{-11} \) for inflationary and causal fields, respectively. They may also be further constrained by future 21 cm observations resulting from CMB temperature fluctuations. (Tashiro & Sugiyama 2006; Sethi & Subramanian 2009).

In this Letter, we entertain the idea that a primordial magnetic field indeed existed and make steps to investigate their impact on first structure formation. In \( \Lambda \text{CDM} \) structure is built bottom up, marginal differences in the formation of the first objects could have significant impact for all subsequent structure formation. Population III stars were formed at \( z > 20 \) in minihalos of mass \( \sim 10^3 - 6 \text{M}_\odot \) that gravitationally collapse via H\(_2\) cooling (Tegmark et al. 1997; Abel et al. 2002). Magnetic fields are understood to impact present-day star formation in a number of ways (McKee & Ostriker 2007). Although the exact nature of their impact on Population III stars is still yet unknown, there have been a number of somewhat idealized studies exploring these effects (McKee et al. 2020), including reducing fragmentation (Sharda et al. 2020), increasing ionization degree (Nakauchi et al. 2019), and angular momentum transport (Machida & Doi 2013). Any weak initial field will be amplified by the small-scale dynamo (Xu et al. 2008; Sur et al. 2010; Schober et al. 2012; Turk et al. 2012; Wagstaff et al. 2014), but tends to not strongly alter the initial collapse forming primordial stars.

On the other hand, Sanati et al. (2020) considered the impact of PMFs on the total matter spectrum and the subsequently formed dwarf galaxies. They ruled out the highest strengths (i.e., 0.2–0.5 nG for inflationary fields) for a number of reasons. First, the dwarf galaxies in these cases overproduce stars, in contrast to local scaling relations. They also produce enough ionizing photons to reionize the universe prior to \( z = 9 \), also contradicting numerous other measurements. The properties of
dwarf galaxies depend on the chemodynamical environment that they are embedded within. As a result, these results cannot be fully interpreted without explicitly resolving the minihalo scales where the first objects were formed.

The latter is what we attempt here. In addition, we evolve the matter perturbations and magnetic fields from the linear regime at high redshift considering the earliest collapsing object in a fairly large volume. This is in contrast to Machida & Doi (2013), Nakauchi et al. (2019), McKee et al. (2020), and Sharda et al. (2020), who adopt nonlinear initial conditions at lower redshift. However, we stress that unlike Sanati et al. (2020) we do not take into account the additional power in the baryon density fluctuations generated by the magnetic fields themselves (Wasserman 1978; Kim et al. 1996; Subramanian & Barrow 1998). As in the above-mentioned works, our study cannot ultimately reach definitive conclusions but should add an important element to the discussion. In the following section, we introduce our simulation setup. Then, in section 3, we describe the results. Finally, we discuss potential impact and caveats in section 4.

2. Simulation Setup

Our exploration involves a set of five cosmological simulations using the latest public version of the adaptive mesh refinement ideal MHD simulation code Enzo v2.6 (Bryan et al. 2014; Brummel-Smith et al. 2019). Our basic setup is taken from Koh & Wise (2016) with a nested initial grid focusing on a single minihalo in a 250 $h^{-1}$ comoving kpc box. We consider the same physics as with this earlier study including a nine-species nonequilibrium chemistry model (Abel et al. 1997), a time-dependent Lyman–Werner background (Wise et al. 2012), and a radiative self-shielding model (Wolcott-Green et al. 2011). Our main focus is the evolution of the minihalo prior to self-collapse and thus we terminate the simulation when a maximal refinement level of 15 (a spatial resolution of $\sim 400$ au) is reached and do not follow the subsequent star formation and feedback processes.

In contrast to this earlier study, we modify the following parameters. First, the Jeans length criterion is reduced down to 32 zones per Jeans length. In studies of magnetic field amplification by gravitational turbulence the required minimum for this parameter is 30 to capture the small-scale dynamo (Federrath et al. 2011; Turk et al. 2012).

The central variable of interest is the initial magnetic field strength. We seed the entire simulation domain with a magnetic field initially pointed in the $\hat{z}$-direction. To contextualize the values of the magnetic field strengths chosen, we refer to the speed ratio $v_d/c_s$, where $v_d$ is the Alfvén speed, and $c_s$ is the sound speed, and choose the following ratios for our study: 0.03, 0.30, 0.66, 1.00, and 3.00.

For brevity, we will, in the rest of the Letter, refer to the ratios $<1$, $\sim 1$, and $>1$ as subsonic, transonic, and supersonic ratios, respectively. A speed ratio of 1 then is equivalent to an initial proper B-field strength, $B = v_d * \sqrt{4\pi \rho} = 1.32 \times 10^{-6}$ G at $z=150$, where $\rho$ is the mean density in the box. This field strength corresponds to a comoving field strength of 5.79 $\times 10^{-11}$ G. So the full range of initial comoving field strengths spans $1.75 \times 10^{-12}$ G to $1.73 \times 10^{-10}$ G. The comoving region from which the $\sim 10^6 M_\odot$ halo forms is approximately 10 kpc across and hence is the relevant scale over which we assume the magnetic field to be initially uniform.

3. Results

We analyze the numerical simulations based on full snapshots stored on disk for every 10 Myr of the evolution until the highest level of refinement of 15 is reached for the first time at which the simulation is terminated and a final data output is produced. The exception is the supersonic ratio of 3.0 in which the strong B-field inhibited the collapse and we terminated the simulation at $z = 12.6$.

3.1. Central Halo Inspection

Here we show plots comparing the different runs. Figure 1 shows projection plots of density and temperature of the various runs, each panel spanning 1 kpc across. From left to right, the plots are in order of increasing $v_d/c_s$ ratios, shown at the time when the highest refinement level is reached, corresponding to collapse of the central region. The 0.03 and 0.30 subsonic ratio central halos collapse at $z=15$, the 0.66 halo at $z=14$, and the transonic halo at $z=12.7$. In comparing the two subsonic cases of ratios 0.03 and 0.30 where the collapse times are similar, we can see that the extended filament protruding from the central object is less dense in the greater ratio case. Also, the surrounding satellite gas clouds all have noticeably reduced densities.

As the time of collapse is delayed at higher $v_d/c_s$ ratios, the central region has more time to grow both in size as it merges with the nearby subhalos and in temperature. In particular, for the transonic case where $v_d \sim c_s$, we see an extended temperature cavity where the central halo has collapsed, surrounded by highly heated gas, with temperatures reaching several $T \sim 10^4$ K. The nearby gas clouds to the left and below the central halo in the plane of the plot in the leftmost panel have completely merged with the central halo in the transonic case resulting in significantly elevated temperatures. By the time these clouds merge in, the central halo had already been cooled to form a dense core. The infalling gas then collides with the dense core and is scattered around it producing the extended substructure shown in the plot. In the supersonic case, we see continued heating of the central region of the halo while the density remains quite low and that cooling has not begun even at this late stage.

One significant trend is that the time of collapse is delayed as a function of increasing speed ratio. The additional magnetic pressure heats the gas and adds an additional barrier for the gravity to overcome to initiate self-collapse. This trend is such that the transonic halo already collapses at $z = 12.66$ where the magnetic field is contributing to a delay time of $\Delta z = 2.5$. Following this trend, we estimate that the central halo in the highest ratio run of 3.0 is unlikely to collapse even until $z = 10$ and may only collapse once reaching the atomic cooling limit.

Figure 2 shows the temperature evolution of the highest-density point as a function of redshift for each of the different simulations. As the initial $v_d/c_s$ increases, the peak temperature reached by this point also increases. On the other hand, the minimum temperature reached by this densest point is lowered by a few tens of Kelvin as the ratio is increased. This pattern does not hold true for the ratio of 3 as the object has yet to undergo collapse, but we would expect it to follow the pattern once it does collapse. This rise in temperature not only results in delayed collapse, but we also observe that, once collapse takes place, it is progressively elongated with increasing $v_d/c_s$.
In the case of the supersonic ratio of 3, the halo has not begun to cool even at the final data dump at $z = 12.6$.

Figure 3 shows radial profiles centered around the central halo for a subsonic ratio of 0.03 and a transonic ratio of 1.00. As the overall collapse is delayed, the halo is able to accrete more mass and thus we see a more extended profile in the density plot (upper left). The temperature profile (upper right) shows that the temperature in the core for the transonic halo is a few tens of K cooler but with a more extended heated tail. Surrounding the cool inner region is a hot gas that is heated to over $1000^\circ$ greater in the transonic halo. As the profile is spherically averaged, the actual temperatures in the heated region reach several thousand Kelvin. The neutral H$_2$ fraction (lower right) shows a corresponding extended profile for the transonic case as the gas clouds that harbored the molecular cloud in the subsonic cases have been merged into the central object.

Inspecting the collapsed region in detail shows that the nature of the collapse itself has changed drastically between the two cases. In the subsonic cases, the central halo undergoes a mostly self-similar spherical collapse. On the other hand, the collapse in the transonic halo proceeds along a particular axis along a filamentary structure. This results in a vastly different substructure particularly noticeable in the H II fraction profile. The ion fraction shows a pronounced increase by a couple orders of magnitude in the available ions in the cool region surrounding the central heated core. Figure 3 also includes a projection of the ion fraction for the transonic case as weighted by density spanning 10 pc to show the asymmetric nature of the collapse.

3.2. Magnetic Field Evolution

We now present the behavior of the magnetic fields in our simulation.

Figure 4 shows phase diagrams of comoving magnetic field strength versus the baryon overdensity in a sphere of radius 1 kpc surrounding densest cell in the transonic run. The red line follows the mass-weighted average magnetic field strengths. The dotted line shows $B \propto \rho^{2/3}$, where $\rho$ is density, which is the scaling for the magnetic field amplification in the case of a ideal spherical collapse, or compressional amplification. In the subsonic scenario, there is still evidence of small-scale dynamo driven amplification shown by the red line growing steeper than the dotted line, noting that it is muted relative to scenarios where $v_a/c_s << 1$. On the other hand, in the transonic case, the collapse is not driving strong amplification, and in fact the field is even less amplified than expected during ideal compression. The latter implies that much of the collapse must be occurring along the field lines, rather than squeezing lines together to drive amplification. This is supported by the projection plot in Figure 3, where the collapse was no longer spherical and had a preferential axis. Furthermore, the field is effectively saturated having reached corresponding energies comparable to the kinetic energy in the system. And in fact, in this particular scenario, the magnetic energy is comparable to the kinetic component in this entire domain.

Figure 5 shows a projection plot of the plasma $\beta$, which is the ratio of the thermal pressure to the magnetic pressure for the
transonic case. The magnetic fields are overplotted as streamlines and show that the initial magnetic field that was initialized in the \( z \)-direction is still coherent across the halo that is formed. Within the halo, the turbulent collapse of the gas pulls the field lines with it and reorders them.

Figure 6 shows the \( v_a/c_s \) ratio at the highest-density point as a function of redshift for all the simulations. There is a ceiling for this ratio in the core of the central halo at \( v_a/c_s \sim 10 \). For the subsonic cases, the magnetic field is rapidly amplified to approach this limit. As the initial field strength is increased, the degree of amplification is reduced overall and the ratio reaches a plateau. This corresponds again to the saturation point that is in agreement with the amplification saturation observed by Latif et al. (2014) and Sharda et al. (2020).

4. Conclusions and Discussion

In this Letter, we followed the collapse of the first minihalos in cosmological simulations in the presence of primordial magnetic fields of comoving strengths in the range \( \sim 2 \times 10^{-12} - 2 \times 10^{-10} \) G. We find that when fields are of order \( 5 \times 10^{-11} \) G or larger, corresponding to the Alfven speed being of the same order or larger than the sound speed at high redshift \( z \gtrsim 100 \), the formation of first stars in such minihalos is significantly impacted. In particular:

1. With increasing initial magnetic field strength, the collapse of minihalos due to the \( \text{H}_2 \) cooling is progressively delayed both in duration and final time of collapse.

2. Magnetic field amplification by the small-scale dynamo and by simple flux-freezing during spherical collapse is increasingly reduced with increasing field strength.

3. At high B-field strengths, \( \text{H}_2 \)-cooling-induced collapse can potentially be completely suppressed.

4. Magnetic fields lead to asymmetric gravitational collapse and an elevated ion population in the central few parsecs of the minihalo.

5. For all magnetic field strengths investigated, the Alfven-to sound-speed ratio in the center of the minihalos saturates at \( v_a/c_s \sim 10 \), with saturation occurring earlier for stronger initial fields.

Our findings could have profound implications for early universe structure formation and beyond. First of all, the minimum collapse mass scale would be greatly sensitive to this effect as the magnetic fields suppress collapse in smaller minihalos. This can impact the initial mass function of primordial stars and the resulting chemical evolution of the universe. The presence of larger pristine gas reservoirs by the time of collapse can result in radically different star formation scenarios. It can also perhaps more readily facilitate more exotic formation scenarios such as direct-collapse black holes.

We caution, though, that our study has not included all relevant effects. Apart from the neglect of ambipolar diffusion, a serious limitation is the neglect of enhanced baryonic density perturbations induced by the magnetic fields themselves. When taken into account, it may well be that, rather than being delayed, star formation may occur earlier than in the no initial magnetic field counterpart. This is due to the enhanced power...
on small scales making minihalos collapse earlier. However, we believe that most other effects found in this study should remain and possibly lead to more massive first stars.

To place our findings into context, either inflationary-produced PMFs or phase-transition-produced PMFs could relieve the Hubble tension. In both cases a pre-recombination field strength of $\sim 5 \times 10^{-11}$ G is required. However, whereas in the former scenario this field strength is kept to the present epoch, in the latter scenario fields are subject to further damping down to $1 \times 10^{-11}$ G through the epoch of recombination. Coincidentally this is approximately the strength required to explain cluster magnetic fields to be entirely primordial. We may therefore conclude that only inflationary-produced PMFs may influence first structure formation, whereas phase-transition-produced fields are too weak to have significant impact.

This work was performed using the open-source Enzo and YT codes, which are the products of collaborative efforts of many independent scientists from institutions around the world. Their commitment to open science has helped make this work possible. This work was supported in part by the U.S. Department of Energy SLAC Contract No. DE-AC02-76SF00515.

Software: Enzo (Bryan et al. 2014), YT (Turk et al. 2011).

Figure 4. Phase plot of the comoving magnetic field strength against baryon overdensity within a sphere of 1 kpc surrounding the densest point. The left shows the subsonic ratio of 0.03, while the right shows 1.00. Red line indicates the average field strength, while the dotted line is a $B \propto \rho^{2/3}$ reference trendline representing the ideal magnetized spherical collapse. While the subsonic case suggests some turbulent amplification, the transonic halo is not even matching the compressional amplification. This further suggests that the gravitational collapse is occurring along the field lines.

Figure 5. Projection plot of plasma $\beta$ weighted by density centered around the central object spanning 1 kpc across in the transonic case. The streamlines trace the magnetic fields and show the coherence of the initial magnetic field oriented in the z-direction over the span of the figure. In a large fraction of the total region, the magnetic pressure dominates over the thermal pressure.

Figure 6. Plot of the $v_a/c_s$ ratio at the cell with the highest density as a function of redshift for all simulations. At subsonic ratios, the small-scale dynamo driven amplification rapidly increases this ratio. As the initial ratio is increased, the amplification is suppressed and the ratio near the center of the halo stays near $v_a/c_s \sim 10$. 

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