Magnetic Field Generation During the Formation of the First Stars

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Abstract. Recent advances in numerical simulations of cosmological structure formation have revealed the ubiquity of turbulence in the early Universe suggesting that the primordial gas is highly turbulent during the formation of the first stars. This has strong implications on the generation of magnetic fields via small-scale dynamo action. Using high-resolution numerical simulations, we show that the turbulence is driven by the gravitational collapse on scales of the order of the local Jeans length, which leads to an exponential amplification of the magnetic field by the small-scale dynamo. The field amplification by the dynamo is stronger than the amplification that could be achieved by pure gravitational compression of the field lines. We find that the presence of the small-scale dynamo can only be identified in numerical simulations where the turbulent motions in the central collapsing core are resolved by at least 32 grid cells.

1. Magnetic field generation during gravitational collapse

We focus on the gravitational collapse and magnetic field amplification of the baryon-dominated inner parts of a collapsing primordial halo. Dynamo amplification of weak initial seed fields during the formation of the first stars has been previously addressed using semi-analytic models (Schleicher et al. 2010). In this contribution, we present results obtained from three-dimensional numerical simulations. The initial conditions of our simulations motivated from the cosmological models of Abel et al. (2002), Yoshida et al. (2008) and Bromm et al. (2002) correspond to a turbulent, magnetized Bonnor-Ebert sphere. For more details on the numerical setup and initial conditions, the readers are referred to Sur et al. (2010). The efficiency of the dynamo process depends on the Reynolds number and is thus related to how well the turbulent motions are resolved Haugen et al. (2004); Balsara et al. (2004). Higher resolution yields larger field amplification. We report results obtained from five numerical simulations where we resolve the local Jeans length $\lambda_J$ by 8, 16, 32, 64 and 128 cells.
2. Results

Fig. 1 shows a snapshot of the central region of the collapsing core in our highest-resolution simulation at a time when the central density has increased by a factor of \( \sim 10^6 \). Starting from a weak 1 nG field, the magnetic field grows by a factor of \( 10^6 \), reaching a peak value of about 1 mG in the central core at \( \tau \sim 12 \) as shown in Fig. 2a. Here, \( \tau \) is a dimensionless time coordinate normalized in terms of the local free-fall time (see Eq. 2 in Sur et al. (2010)). As shown in Fig. 2b, the field amplification is indeed stronger than what is expected from pure flux-freezing. This indicates that the small-scale dynamo provides significant additional amplification over compression during the birth of the first stars. Compressible motions generated during the contraction are converted into solenoidal, turbulent motions during the collapse. In Fig. 3.1, we plot the velocity spectra at different times by subtracting out the radial infall motions. We find that the energy injection scale of gravity-driven turbulence is close to the local Jeans scale (Federrath et al. 2011). While the turbulence is decaying (\( \tau \leq 4 \)), the initial spectrum following \( k^{-2} \) flattens slightly and turns into the Kolmogorov (1941) spectrum, \( P(k) \propto k^{-5/3} \), consistent with the expectation for subsonic, hydrodynamic turbulence. The magnetic field grows most efficiently on the smallest scales (see Fig. 3.2), for which the stretching, twisting, and folding of field lines, and the turbulent vortices are sufficiently resolved. The peak of the initial magnetic spectrum at about \( k/k_J = 1.4 \) quickly shifts to smaller scales and stays roughly constant at \( k/k_J \approx 4 - 6 \) for \( \tau \geq 4 \). We find that this scale corresponds to about 20 - 30 grid cells in the simulations.

3. Conclusions and Discussions

In summary, we conclude that the ubiquity of turbulence in the primordial minihalo can lead to the generation of strong magnetic fields by the small-scale turbulent dynamo.
Figure 2. Evolution of the dynamical quantities in the central Jeans volume as a function of $\tau$, for five runs with different number of cells to resolve the local Jeans length. Panel (a) shows the rms magnetic field strength $B_{\text{rms}}$, (b) the evolution of $B_{\text{rms}}/\rho_m^{2/3}$, showing the turbulent dynamo amplification by dividing out the maximum possible amplification due to perfect flux freezing, (c) the evolution of the mean density $\rho_m$ and (d) the rms velocity $v_{\text{rms}}$. The runaway collapse commences at about $\tau \sim 4$.

Figure 3. **Left (Fig. 3.1):** Time evolution of the radial infall subtracted velocity power spectra normalized to the local Jeans wavenumber, $k = k_J$ inside the core for different times until $\tau = 12$. **Right (Fig. 3.2):** Time evolution of the magnetic field spectra until $\tau = 12$. The data for both these plots are obtained from a simulation run with a resolution of 128 cells per Jeans length.
action. We find in our highest resolution simulation that a weak seed field of $\sim 1$ nG, is amplified to about 1 mG strength in the central collapsing core during the formation of the first stars. The small-scale dynamo only works in simulations in which the turbulent motions within the local Jeans length are resolved by at least 32 cells.

This generation of strong magnetic fields has interesting consequences for our understanding of how the first stars form and how they influence subsequent cosmic evolution. Recent hydrodynamical simulations Clark et al. (2010) suggest that the primordial gas is highly susceptible to fragmentation even for subsonic turbulence. Magnetic fields can significantly influence this scenario provided they are amplified to values close to equipartition. To investigate the role of magnetic fields in influencing the fragmentation properties of the primordial cloud, it is necessary to evolve our existing simulations beyond the exponential growth phase. This will help us to gain an insight on the saturated field strengths to be expected in the protostellar core of the first stars. The results obtained from this work lends a strong support to the dynamo amplification of weak initial seed magnetic fields by the underlying turbulence and underlines the importance of magnetic fields during the formation of the first stars. However, this paradigm needs to be tested against a broad range of parameters, which depend, in particular on the properties of turbulence and the global rotation of the primordial cloud.

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