Primordial magnetic fields: Impact on reionization and the first stars

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Introduction

Primordial magnetic fields are predicted in numerous theoretical models for inflation, the electroweak phase transition, the QCD phase transition or even the epoch of recombination (see Grasso & Rubinstein (2001) for a review). In this presence of non-zero helicity, magnetic power may be shifted to larger scales via the inverse cascade (Banerjee & Jedamzik 2004).

In this work, we explore the putative effects of such magnetic fields on reionization and the formation of the first stars. This is due to ideal MHD effects like magnetic pressure and tension, but also non-ideal MHD effects like ambipolar diffusion. The latter is due to the imperfect coupling with the neutral gas after recombination and leads to the dissipation of strong magnetic fields. We briefly discuss additional work concerning the generation of magnetic fields in atomic cooling halos via dynamo effects. Such magnetic fields could help to suppress fragmentation and form more massive stars.

Influence on large scales and reionization.

Magnetic fields can influence the postrecombination universe via

- Magnetic pressure
- Magnetic tension
- Non-ideal MHD effects like ambipolar diffusion

We follow the evolution of magnetic fields, gas temperature and chemistry in the postrecombination epoch until the formation of a virialized halo at $z = 20$ (Schleicher et al. 2009). We find the following results:

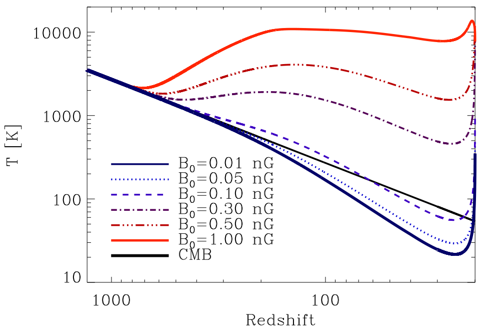

Fig. 1: Evolution of the gas temperature.

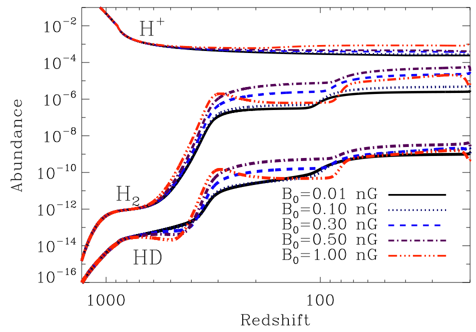

Fig. 2: Evolution of chemical species.

Due to magnetic energy dissipation, the gas temperature may increase up to $\sim 10^4$ K. At this temperature, Lyman α cooling gets efficient and balances the additional heat input, while collisional ionization becomes efficient as well and decreases the efficiency of ambipolar diffusion. The increased gas temperature and electron abundance stimulates the formation of molecules, in particular the main coolants H_2 and HD. The gas can therefore cool more efficiently when it reaches higher densities.

Implications on characteristic mass scales and reionization.

While the effects of ambipolar diffusion heating affect the thermal Jeans mass via the gas temperature, magnetic pressure further gives rise to a magnetic Jeans mass, which may counteract gravitational collapse via magnetic pressure. The magnetic Jeans mass decreases with time as the magnetic energy is dissipated. The increase of the Jeans mass may prevent gravitational collapse in the first minihalos.

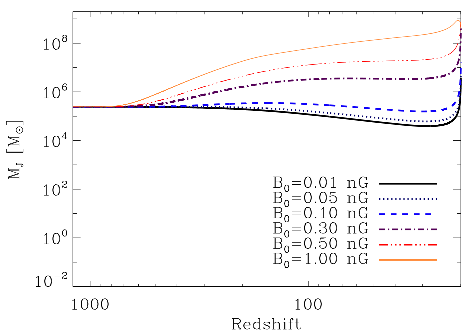

Fig. 3: Evolution of thermal Jeans mass.

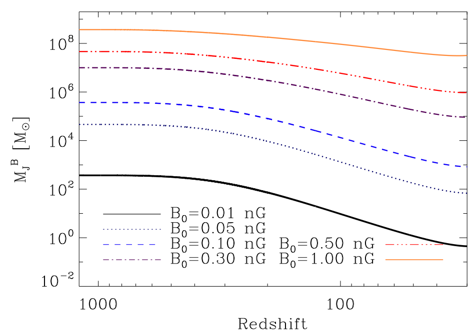

Fig. 4: Evolution of magnetic Jeans mass.

To explore the consequences of such an increased Jeans mass in more detail, we have implemented these effects in a semi-analytic model for reionization and calculated the expected reionization optical depth as a function of the comoving field strength and star formation efficiency for different stellar models (Schleicher, Banerjee & Klessen 2008), thus constraining the primordial field strength.

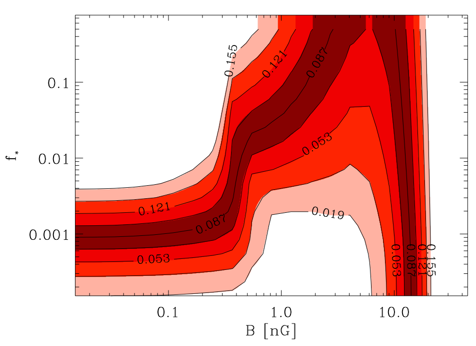

Fig. 5: Reionization optical depth for Pop. III stars.

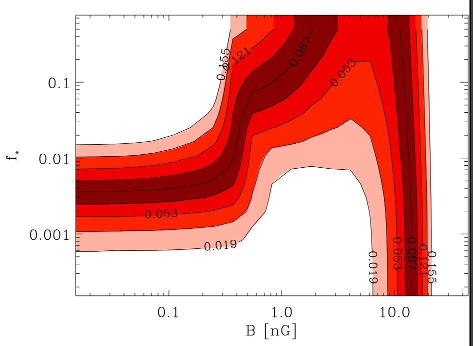

Fig. 6: Results for a mixed population.

The dark-red shaded region shows the 1σ range of the WMAP 5 data.

Primordial star formation in the presence of magnetic fields.

We model protostellar collapse in the presence of magnetic fields with the one-zone model of Glover & Savin (2009), which accurately describes the thermal evolution as well as the abundances of the ionized species in the gas. The latter is particularly important for an accurate calculation of the ambipolar diffusion heating rate. We have extended their model in the following ways:

- Use initial conditions corresponding to the large-scale calculations presented on the left.
- Calculate ambipolar diffusion heating rate from the species abundances with the multi-fluid model of Pinto et al. (2008) with the momentum transfer coefficients of Pinto & Galli (2008).
- Calculate evolution of magnetic field strength with density based on simulations of Machida et al. (2006), but correct them for the effect of ambipolar diffusion.
- Follow the evolution of the thermal and magnetic Jeans mass.

Results and implications.

With this approach, we find the following results for the thermal and chemical evolution during the protostellar collapse phase:

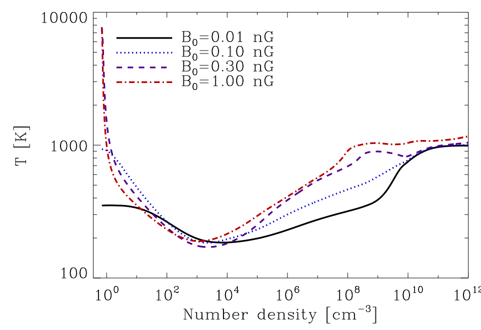

Fig. 7: Temperature evolution.

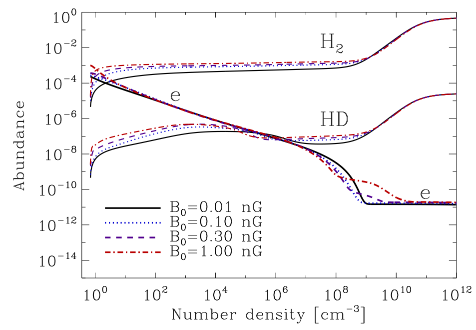

Fig. 8: Evolution of chemical abundances.

This leads us to the following conclusions:

- Primordial magnetic fields can heat the IGM gas up to 10^4 K.
- They may increase the abundance of molecules in primordial gas.
- They may considerably increase the Jeans mass in the IGM, therefore suppressing star formation in small minihalos.
- During protostellar collapse, they do not affect the temperature minimum and the fragmentation mass scale.
- However, they increase the temperature at densities beyond the temperature minimum, giving rise to larger accretion rates onto the protostar.
- As shown by Machida et al. (2006), the formation of jets can change the final protostellar mass by 10%. We expect, however, that this will be compensated due to the higher accretion rates from the increased temperature.

Current and future work.

Magnetic fields may not only be created in the early universe, but also within the first objects due to dynamo effects. Prelimary studies indicate that such dynamos are very efficient in atomic cooling halos and may lead to magnetic energies corresponding to $\sim 10\%$ of the kinetic energy. Such magnetic fields could potentially suppress fragmentation and binary formation.

References

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