Abstract

This proposal will focus on the influence the magnetic fields should have on the dynamics of perturbations in an isotropic and homogeneous Universe, addressing the evolutive region from the nucleosynthesis of light elements up to the recombination of atomic hydrogen, with particular attention to the matter-dominated era. In fact, during these epochs the Universe is characterized by a plasma structure, whose composition is well approximated by electrons and protons. The scheme of investigation will regard the simultaneous analysis of the magnetic field self-consistent generation and their relative influence on the primordial inhomogeneity dynamics outlining the coupling of the Boltzmann equation to the Einstein-Maxwell ones (BEM-system) with the main objective to overcome a dichotomy among current approaches. In fact, on the one hand several studies focus on the generation of a non-vanishing magnetic field from microphysical processes, on the other hand different analyses address how the presence of an assigned background magnetic field affects the cosmological evolution of inhomogeneities. A self-consistent picture starting from a kinetic description is, however, still lacking.

The main goal of the proposed research line is to unify these two different issues in a coherent scheme, in order to characterize the real correlation processes in the Universe phenomenology as arising from the plasma nature of the cosmological fluid. In this respect, the magnetohydrodynamics (MHD) and kinematics analyses of the primordial thermal bath must be performed in the framework of the Standard Cosmological Model, and this activity will state whether plasma configurations exist such that sufficiently strong magnetic fields can be generated in order to influence the formation of large-scale structures. This investigation line will be firstly tested in a Newtonian framework, where some specific results have already been outlined [1, 2], and then applied to regimes of cosmological gravitational field and relativistic matter sources, together with the development of the related numerical algorithms.

As final step, the characterization of the fundamental parameters of the model will be addressed through the analysis of cosmological observations, pursuing the investigation of the temperature and polarization anisotropies of the Cosmic Microwave Background Radiation (CMBR). In particular, in addition to the B (*i.e.*, curl)-type polarization fluctuations directly sourced by the anisotropic stress of the field, the same field also induces a Faraday rotation of the CMBR polarization. This results in the creation of "spurious" B-modes from the rotation of the E (*i.e.*, gradient)-type component of the polarization field [3]. The spectra of the direct and Faraday-induced fluctuations peak at different angular scales, leading to a unique signature. Moreover, since the amount of Faraday rotation is frequency-dependent, another detection strategy corresponds to the comparison of the CMBR polarization vector in a given direction at two distinct frequencies [4]. The temperature anisotropies of the CMBR, down to very small angular scales, have been recently measured with exquisite precision by the Planck satellite [5]. These observations

have been used by the Planck collaboration themselves to constrain the amplitude of primordial magnetic fields [6]. The Planck collaboration did not release the polarization data, but these are expected with the second major release that will take place in 2014. As noted above, small-scale polarization is a very promising tool to constrain the properties of cosmological magnetic fields. In addition to Planck, polarization measurements will be pushed, in the near future, to even smaller scales by experiments like ACTPol [7] and SPTPol [8].

Detailed Description of the Project

Present Status of the Topic: Magnetic fields are everywhere in the Universe [9, 10]. Inside many spiral galaxies, including the Milky Way, there are coherent magnetic fields of the order of micro Gauss and the galaxy formation results possibly influenced by magnetic forces, since even stronger fields exist in the intra-cluster medium. Moreover, observations of high redshift quasars suggest that significantly strong magnetic fields could be already present in protogalaxies.

The precise origin of galactic and extra-galactic magnetic fields is an outstanding problem in modern cosmology [11]. One hypothesis suggests the amplification of very weak magnetic fields through the MHD galactic dynamo mechanism [12] (by conversion of turbulent motion kinetic energy into magnetic energy) although the efficiency of such a mechanism has not yet a shared consensus and it is not able to explain the existence of intra-cluster magnetic fields. The main alternative lies on the proposal that magnetic fields come directly out from the amplification of primeval fields (see [11] and refs. therein) following the adiabatic compression during the collapse of the protogalactic cloud. In fact, the conservation of magnetic flux in the intra-cluster medium implies that the magnetic field increases proportionally inverse of to the surface enclosing the system. Both mechanisms rely on the existence of a seed field, which could be as low as 10^{-30} Gauss [13] in the case of the dynamo, or larger than about 10^{-10} Gauss in the case of the adiabatic compression. In particular, we underline that the latter value is compatible with the observational limit given by the intra-cluster medium and with the Big Bang nucleosynthesis constraint.

Also the origin of the primeval seeds has still to be consistently identified. In fact, such small magnetic fields could be generated by astrophysical batteries in relatively recent times, but this would imply a different mechanism for the generation of galactic and intra-galactic magnetic fields. In particular, for what concerns magnetic fields created during the radiation-dominated era (*i.e.*, after inflation), they result to have too small coherence lengths which, in turns, would destabilize the dynamo [14, 15]; at the same time, fields surviving an epoch of inflationary expansion are usually too weak for sustaining such a process. Furthermore, primordial magnetic fields are constrained by several astrophysical and cosmological observations: the present strength of a large scale and homogeneous magnetic field results to be less than about 10^{-9} Gauss [16], while a random and small scale field could be thousand times stronger.

The effects that large scale micro Gauss magnetic fields can have on the evolution of cosmological structures have been instead rather extensively studied. The presence of large scale fields in a homogeneous and isotropic Universe has been considered in a fully relativistic framework (see [17] for a recent example related to the dark energy issue), while studies on inhomogeneous cosmologies, dealing with the influence on galaxy formation, have been mainly performed in a

Newtonian scheme until recently [18]. Moreover, in the past few years fully relativistic treatments of such an inhomogeneous magnetic cosmological scenario have been also developed (see [19] and refs. therein). Concluding, it is worth noting that magnetic fields generate density and vorticity perturbations and the perturbative evolution equations cannot be analytically solved requiring also numerical analyses.

Characterization of the Research Line: The present proposal will be mainly aimed of understanding the interactions between cosmological magnetic fields and the dynamics of primordial perturbations. In particular, on the one hand we will assess whether cosmological magnetic fields can be self-consistently generated as a by-product of the evolution of the plasma component perturbations. On the other hand, we will study and clarify the back-reaction of these magnetic fields on the perturbations themselves.

We argue that the cosmological plasma is a multi-scale system, involving firstly the global dynamics, secondly the micro-scale plasma fluctuations and finally the possible meso-scale turbulence. More specifically, the role that a magnetic field can play in the early Universe at MHD level is essentially related to the introduction of a privileged direction in the gravitational collapse of the mass density perturbations [1, 2]. This anisotropic feature can not influence the expanding isotropic background as far as the energy density of the magnetic field is much smaller than the Universe mass density, but it affects significantly the Jeans mechanism [20, 21] for the structure formation. As mentioned above, our analysis will be pursued, as first step, in the framework characterized by the presence of an external homogeneous magnetic field, whose perturbations are self-consistently fixed to the full plasma equilibrium. Since the influence of the plasma features on the early Universe gravitational instability have been followed in some details in the linear paradigm (to fix the spectrum of the instabilities) [1], the quasi-linear growth of the perturbations will be investigated to characterize the onset of non-linear behaviors, especially when small scales are considered. Moreover, we will focus our attention both on the generation of the electrostatic turbulence and on the influence of dissipative effects (resistivity and viscosity) on the perturbation growth.

The majority of current approaches have either considered the magnetic field as an external field, or have neglected the kinetic properties of the plasma, using the fluid approximation and consequently neglecting pure plasma effects. The research that we intend to carry on will involve the study of the coupled BEM-system on a Friedmann-Lemaître-Robertson-Walker (FLRW) background. We will mainly focus on scalar and vector perturbations, with the aim of studying the era between the nucleosynthesis of the light elements and hydrogen recombination, when the Universe is well described by a plasma of electrons and protons. We will first characterize the behavior of the plasma in regimes where an analytical or semi-analytical treatment of the BEM-system is feasible (for example, at scales much below the cosmological horizon, where Newtonian gravity is a good approximation), in order to gain a clear physical understanding of the relevant phenomena and to compare our analyses with respect to existing results. This will be particularly useful for the study of the stability issue, at cosmological time scales, of the plasma inhomogeneities (*i.e.*, the equivalent of the Jeans mechanism). Once a satisfactory understanding will be reached, we will address the numerical solution of the BEM-system in the general case. This will be used to assess the relevance of the plasma structure in the evolution of the cosmological perturbations and to check if the existence of particular plasma configurations can allow the creation of magnetic fields sufficiently strong to influence the later perturbation evolution. We plan to implement the BEM-system in the computer codes used to calculate the anisotropy spectrum of the CMBR, like CAMB. The CMBR spectrum generated by a given plasma profile can be compared to the observations in order to constraint the space of allowed configurations.

Main Goals: The study of cosmological plasma we propose in this project is aimed of characterizing the impact of a relatively small magnetic field on the dynamics of an inhomogeneous perturbation. We will get specific issues in both paradigms of an external background magnetic field and of a random self-consistent magnetic profile. This will lead to a reformulation of the problem of Universe Jeans-like gravitational instability in terms of the plasma features emerging in the evolution of the fundamental constituents of the primordial thermal bath. In fact, the MHD approach outlines important modifications induced by the magnetic pressure and tension on the stability of over-dense regions across the expanding space [1]. The former provides a mainly isotropic contribution, able to increase the value of the Jeans length, while the latter is a term depending on the magnetic field direction and introduces a degree of anisotropy into the dynamics of the collapse. This last feature will allow to verify if the presence of an external field can explain the filaments of matter, reliably observed in present surveys of structures in the Universe. In particular, there are indications in favor of components of Universe matter distribution, whose dimensionality should be close to a fractal profile of index about two. Such a tendency to form planar structures is one of the expected consequences of the magnetic field presence and it will be quantitatively checked in our analysis.

We will furthermore estimate the relevance of the electrostatic turbulence in accelerating the onset of the non-linear growth of perturbations. This topic is probably the most intriguing that we will address, since it could lead to a revised treatment of the primordial inhomogeneities in the cosmological medium, especially when sufficiently small scales are taken into account. Our results will be compared with the observations of the CMBR by current and forthcoming experiments. Since the influence of the magnetic field is expected to be relevant at small scales, the comparison of our predictions with the present and incoming data from the Planck satellite (which is exploring the inhomogeneities of the black body temperature at very high multipoles) will be of particular impact.

From the kinetic point of view, we will implement scenarios of magnetic field generation in the framework of a collisional Boltzmann equation in order to describe the primordial plasma where particle interactions are taken into account in a self-consistent scheme. It will be crucial to compare the results of this kinetic description with the MHD scenario, in order to trace when and why the single-fluid description breaks down in the cosmological framework. The most relevant issues and differences between the two approaches (kinetic and MHD) are expected in the case of a fully general relativistic analysis and in those situations corresponding to phase transition of the Universe (for instance very close to the recombination era). The possibility to self-consistently generate a magnetic field inside the plasma, by virtue of its natural instabilities, is particularly promising at very small scales. In this respect, the observations of the Planck satellite, once matched with our issues, will provide precise constraints on the possible amplitude of these transient magnetic fields.

Required Resources: The development of the present project requires the participation of two young researchers who will face, in parallel, different tasks of the proposal with integrated and, to some extent, complementary competences.

One of these two researchers must be a postdoctoral fellow, having a solid background on the cosmological setting and an appreciable experience on plasma physics. This fellow has to deal with the set up of the self-consistent BEM-system algorithm, focusing his attention on the generation of magnetic field within the primordial plasma. The recruitment of the postdoctoral fellow will be pursued by granting an official application managed by an Italian Physics Department that will be interested to host the development of this research line.

The second researcher should be a Ph.D. student who, after an initial period of formation, will address the question concerning the evolution of the primordial perturbations in a self-consistent scheme, both developing the numerical simulations of the resulting CMBR spectra and analyzing the role played by the electrostatic turbulence on the meso-scales. The recruitment of this Ph.D. student will be pursued by financing a Grant within the joint Ph.D. School "Astronomy, Astrophysics and Space Science", between the Universities of Rome "Sapienza" and "Tor Vergata".

The resources necessary to these recruitments would have to be integrated by the support of activities devoted to the diffusion of the obtained scientific results. In particular, during the project, the Association "Lo Spazio nel Tempo" plans to organize a workshop concerning to the topic of the project, in order to enlarge and enforce the synergy among different research groups toward the study of Plasma Cosmology.

References:

[1] M. Lattanzi, N. Carlevaro, G. Montani, *Phys. Lett. B* **718**, 255 (2012).
[2] D. Pugliese, N. Carlevaro, M. Lattanzi, G. Montani, *Physica D* **241**, 721 (2012).
[3] A. Kosowsky et al., *Phys. Rev. D* **71**, 043006 (2005).
[4] A. Loeb, A. Kosowsky, *ApJ* **469**, 1 (1996).
[5] Planck Collaboration, *Planck 2013 results. I: Overview of products and scientific results*, arXiv:1303.5062.
[6] Planck Collaboration, *Planck 2013 results. XVI: Cosmological parameters*, arXiv:1303.5076.
[7] M.D. Niemack et al., *Proc. SPIE* **7741**, 77411S (2010).
[8] J.E. Austermann et al., *Proc. SPIE* **8452**, 84520E (2012).
[9] P.P. Kronberg, *Rep. Prog. Phys.* **57**, 325 (1994).
[10] C.L. Carilli, G.B. Taylor, *Ann. Rev. Astron. Astrophys.* **40**, 319 (2002).
[11] D. Grasso, H.R. Rubinstein, *Phys. Rep.* **384**, 163 (2001).
[12] A. Brandenburg, K. Subramanian, *Phys. Rep.* **417**, 1 (2005).
[13] A.-C. Davis, M.Lilley, O. Tornkvist, *Phys. Rev. D* **60**, 021301 (1999).
[14] T. Kobayashi, R. Maartens, K. Takahashi, *Phys. Rev. D* **75**, 103501 (2007).
[15] A.A. Schekochihin et al., *Mon. Not. R. Astron. Soc.* **398**, 1970 (2009).
[16] J.D. Barrow, P.G. Ferreira, J. Silk, *Phys. Rev. Lett.* **78**, 3610 (1997).
[17] E.J. King, P. Coles, *Class. Quant. Grav.* **24**, 2061 (2007).
[18] L. Vlahos et al., *ApJ* **629**, L9 (2005).
[19] J.D. Barrow, R. Maartens, C.G. Tsagas, *Phys. Rep.* **449**, 131 (2007).
[20] S. Wienberg, *ApJ* **168**, 175 (1971).
[21] J.H. Jeans, *Phil. Trans. Roy. Soc. London A* **199**, 1 (1902).