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Cosmic magnetic fields

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Magnetic fields are omnipresent in all elements of the Large Scale Structure (LSS) of the Universe, from weak in voids to strong in starburst galaxies (1) (2) (3) (4). In galaxies and clusters of galaxies, the strong field is produced by amplifying an initial “seed” field, by compression and dynamo mechanisms (4). There are at least two possible origins for the initial seed field: it might be primordial of origin, or it can be produced at the epoch of galaxy formation (2) (5). Wash-out of baryons from galaxies which deposits baryons into the intergalactic medium also spreads magnetic field in the LSS elements, because the galactic winds and active galactic nuclei (AGN) driven outflows are most probably magnetized (6) (7). As a result, intergalactic magnetic field (IGMF) which resides in the voids and filaments of the LSS could be *(A)* of primordial origin (2) (3) or *(B)* produced at the epoch of structure formation (2) (5) or *(C)* be the result of "baryonic feedback" process (6) (8). Measurements of IGMF could distinguish between these three possibilities and provide useful insights into the physics of the Universe.

IGMF could be probed by several observational techniques. First, radio signal of distant AGN is subject to Faraday rotation (1) (9). Faraday rotation measurements are most sensitive to the magnetic field in the filaments of the cosmic web, and at the outskirts of galaxies. They yield a correlation length dependent upper bound on IGMF strength at the level of several nano-Gauss (9). Second, gamma-ray observations of AGN allow to measure IGMF through detection of delayed and extended emission, induced by development of electromagnetic cascade along the gamma-ray beam and deflections of cascade electrons and positrons by the magnetic fields in voids (10) (11) (12). The gamma-ray measurement method was pioneered by proposers of this project, by developing a method summarized in Ref. (13) (14) and reporting for the first time the lower bound on IGMF strength at the level of ~10^{-16} G (11). If IGMF is the relic field from the Early Universe, it could leave a trace in the anisotropies and polarization of the cosmic microwave background (CMB). Non-detection of this imprint constrains the void field strength to be lower than several nano-Gauss (15). Finally, ultra-high energy cosmic rays (UHECR) are deflected by IGMF. The field is expected to shape the pattern of arrival directions of UHECR originating from isolates sources. Once the statistics of UHECR signal will be sufficiently high for detection of first isolated sources, UHECR data will be useful for IGMF measurements (14). The IGMF imprint on the signal of the Faraday rotation and UHECR deflection measurements is subdominant compared to the signal produced by the Galactic magnetic field. Because of this, both methods have to rely on a modelling of the Galactic magnetic field which suffers from large uncertainties (16) (17) (18).

Sensitivity of radio, gamma-ray and UHECR approaches could be crucially improved if a model of the IGMF structure along the lines of sight to individual sources (radio galaxies, blazars, UHECR sources) would be available (19) (20). Such model could be worked out based on the magneto-hydro-dynamics modelling of the structure formation process (7) (21) (22) within simulations reproducing the observed structures within several hundred Mpc around Milky Way. The detailed model of magnetic field profile along the lines of sight to the observed sources could be considered in the modeling of propagation and interactions of high-energy particles on the way from the sources toward telescopes and particle detectors on the Earth (23) (24). The technique is now implemented in publicly available packages (25) (26) (27). Modelling of high-energy particle propagation could be used to work out realistic IGMF dependent spectral and imaging templates of gamma-ray and UHECR signal of distant high-energy active AGN. These templates will have to be incorporated in the multi-messenger analysis of high-energy data. The proposers of this project possess necessary expertise in the domain of multi-messenger (gamma-ray, cosmic ray, neutrino signals) data analysis. In practice, the improved search of IGMF and of its origin has to be implemented within a "holistic" modeling / data analysis chain:

1) Modeling of magnetic field evolution, from the moment of cosmological magnetogenesis to the present epoch, using analytical methods combined with constrained cosmological simulations reproducing the observed LSS in the local Universe;
2) Modeling of propagation of high-energy particles through realistic magnetic field derived from cosmological modeling / simulations
3) Inclusion of numerical models of IGMF-dependent multi-messenger (gamma-ray, UHECR) signal in the analysis of observational data, using likelihood techniques.
4) Use of the next-generation telescopes: gamma-ray telescope CTA, radio telescope SKA, Auger Prime and K-EUSO cosmic ray detectors.

The numerical modeling should allow to estimate magnetic field structure of the nearby Universe, considering baryonic physics and magneto-hydrodynamic processes (using numerical codes like ENZO, RAMSES). The result is in the form of 3D model distributions of dark matter, baryons and IGMF in a region of the size of several hundred megaparsecs around the Milky Way. The model of IGMF has to be fed into the numerical model of propagation of high-energy particles using CRPropa and/or ELMAG and/or TransportCR codes (26) (27) (28). The output of numerical modelling of particle propagation is energy and spatial distribution of charged particles, neutrinos and gamma-rays produced on the way from the source to the Milky Way and arriving at a telescope or detector on Earth. The spectral-spatial template will be immediately used for the search for the IGMF via likelihood analysis of the gamma-ray data of Fermi Large Area Telescope (Fermi/LAT) and HESS, MAGIC, VERITAS, CTA. The gamma-ray technique relies on detection of extended and delayed gamma-ray emission (13-16) from extragalactic sources of very-high-energy (VHE) gamma-rays. Such emission is produced by electrons and positrons deposited by gamma-ray beams of blazars and attenuated by the effect of pair production on the extragalactic background light photons. Electrons / positrons re-emit gamma-rays via inverse Compton scattering of CMB photons after being deflected by IGMF. Secondary inverse Compton emission from the pairs is almost in the same direction as the primary gamma-ray beam and this emission is detectable as extended and delayed emission around the primary point source. The gamma-ray probe of the IGMF has been previously performed to derive lower bound on the strength of magnetic fields in the voids of the LSS (11) (12). The reported bound relies on simplistic modelling of magnetic field structure in the intergalactic medium. Namely, the realistic LSS along the lines of sight to the blazars is not considered. Turbulent nature of magnetic field is modelled within a "cell field" model in which magnetic field is assumed to have constant strength all over several hundred megaparsec distance to the source(s) while its orientation is randomly changing within cells of fixed size which corresponds to the correlation length of the field. Such a model does not correspond to reality. Proper modelling of the field along the line of sight could significantly improve quality of IGMF inference from the gamma-ray measurements. Such measurements will be improved by order of magnitude with future measurements of next generation CTA gamma-ray observatory. In particular, detection of IGMF included in CTA science program. Also it included in dedicated IN2P3 2020 proposal, lead by J.Biteau CTA cosmology project. Improvement of theoretical modeling within this project combined with experimental improvement by CTA will give a hope to detect IGMF.

Next generation observatory Square Kilometer Array (SKA) will revolutionize such measurements by providing very large sample of extragalactic sources with available rotation measure data. 3D IGMF models could be directly used to calculate Faraday rotation signal along the lines of sight toward extragalactic sources (9). The main challenge for derivation of the IGMF measurement is to distinguish the signal from much stronger Faraday rotation induced by the Galactic magnetic field. Detectability of the extragalactic component of the rotation measure signals from AGN on top of the Galactic component with SKA has to be assessed. This could be done via likelihood analysis of the rotation measure data fitting the Galactic and extragalactic map templates for subsets of sources at different redshifts. A principal difference of the IGMF induced Faraday rotation is its dependence on the redshift. We expect that an improvement of the limit on the IGMF strength, or detection of the IGMF will be possible due to the improved modelling of the extragalactic component of the rotation measure signal and use of the richer SKA data (as compared to the data of VLA compiled in Ref. (9).

Still one more possibility to probe the IGMF is via using Ultra-High-Energy Cosmic Rays (UHECR). Realistic 3D models of IGMF could be used to calculate deflections of UHECR and predict patterns of clustering of UHECR events on the sky. Similarly to the Faraday rotation in radio band, IGMF effect on UHECR signal is superimposed onto stronger Galactic magnetic field effect. IGMF induced broadening / distortion of the arrival direction patterns of UHECR could be assessed in combination with the Faraday rotation analysis. Next generation UHECR detectors like Auger Prime and K-EUSO will provide improved statistics of UHECR signal, all-sky exposure and improved measurement of the energy-dependent composition of the UHECR flux. All these features are relevant for the IGMF measurements. Heavy nuclei present in the UHECR flux suffer from stronger deflections, so that clusters of UHECR nuclei around source positions appear on intermediate angular scales. In the nearest future, analysis of the influence of Galactic and intergalactic magnetic field on such clustering has to be performed: in the context of the signal of the Telescope Array "hot spot", an intermediate angular scale excess of UHECR events which could be the brightest detectable UHECR source on the sky (29) and of the Pierre Auger Observatory detection of the intermediate angular scale clustering of UHECR (43). The full-sky mapping of the sphere at ultra-high energies (44) could further help disentangling the relative strength of the sources and how their images are impacted by magnetic deflections.

Different possible scenarios of the origin of the IGMF influence the outcome of the constrained magneto-hydrodynamics simulations in different way (see e.g. (30) (31)), and in turn will produce different effects on gamma-ray and UHECR propagation and on the Faraday rotation signal. The spectral shape of the IGMF power spectrum, which depends on the generation process, influences the lower bound inferred on the IGMF intensity by gamma-ray detections (32). The origin of the IGMF being uncertain, several types of initial conditions for the seed magnetic field have to be considered, i.e. different spectral shapes and correlation scales, corresponding to different classes of production mechanisms. It is challenging, but possible to extract the observational signatures of cosmic magnetogenesis scenario using integration of numerical models into radio, gamma-ray and cosmic ray data analysis, as described above. Under the hypothesis of an IGMF of primordial origin, the most favourable setting, which guarantees the highest IGMF amplitude at large scales, is generation during Inflation (33) (34). Generation processes like primordial phase transitions, operating during a phase of standard, radiation dominated expansion of the early universe, provide magnetic fields that are correlated on much smaller scales. Generation of cosmic magnetic fields in the very early universe during inflation was discussed in Ref. (35), where it was shown that the trace anomaly allows for generation of massless gauge fields at inflationary stage. Magnetic fields could also be generated by electric currents (36), which might appear in the case of local electric asymmetry of the universe and other mechanisms operating in primordial plasma. Strength and correlation length of IGMF, its power spectrum in the present-day Universe are influenced by the details of the cosmic magnetogenesis scenario. Identification of specific observational features linked to the details of this scenario would be of tremendous importance possibly opening a new observational window on the Early Universe and providing probes of the epochs of cosmic logical electroweak and QCD phase transitions of Inflation.

Cosmological magnetic field generation is also directly related to the generation of Stochastic gravitational wave background (SGWB) (37) (38) (39) (33). Now that the era of GW astronomy and cosmology has started, it is timely to reconsider this topic in depth, with the aim of establishing to which level the planned next generation of GW detectors, both Earth-based and space-based, can constrain or detect the presence of a primordial magnetic field. In this context, the space-based interferometer LISA, which has been approved by ESA and is scheduled for mission adoption in 2023, is particularly interesting. The frequency range of LISA spans from 10^{-5} to 0.1 Hz. In the early universe, this corresponds to processes operating around the TeV energy scale. LISA could therefore probe the SGWB signal from a magnetic field generated during the Electroweak Phase Transition, which is an important candidate among primordial magnetogenesis scenarios (2).

Thus key CNRS experimental projects Pierre Auger Observatory, CTA, SKA and LISA together with theoretical effort within this project will allow us to make significant step towards understanding of inter-galactic magnetic fields.

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