Bayesian modeling of the Galactic magnetic field constrained by space and ground-based radio-millimetre and ultra-high energy cosmic ray data

ISSI International Team Proposal

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Summary: Our understanding of Ultra-High Energy Cosmic Rays (UHECR), i.e., particles with energies up to 10^{11} GeV, and of Galactic Magnetic Fields (GMF) is strongly dependent on each other: without knowing the strength and orientation of magnetic fields in and around our Galaxy, it is difficult to perform a reliable search for the sources of UHECR, as these particles may be deflected by the GMF by significant angles. On the other hand, deflections of UHECR probe scales of GMF which are difficult to access by traditional methods, such as analysis of polarized synchrotron radiation. A common analysis of both, theoretical source scenarios of UHECR in comparison to actual measured event arrival directions, and theoretical models of the GMF constrained by astronomical data will offer novel ways for progress in both fields.

We propose to organize a team of international experts with the goal to facilitate interaction in the research activities on the GMF and its impact on UHECR propagation in various groups in particle and astrophysics. Employing parametric and non-parametric Bayesian approaches we want to discuss and explore methods to constrain GMF models by all available data, which will largely improve in the next years due to, e.g., Planck polarized maps, Pulsar surveys, LOFAR results and the ever increasing UHECR statistics. Exemplary of the long-term goals of our project, would be to promote the development of a UHECR likelihood function, utilizing the information contained in individual UHECR air showers, multi-messenger indicators as gamma rays and neutrinos, and categorized and parametrized source models for the acceleration of UHECR. To accommodate future developments in theory and observations, we propose to design a common software standard allowing to combine existing codes, libraries and data-formats of individual research groups and experimental collaborations.

We propose to set up an international team of 12 distinguished scientists representing both, traditionally largely separated communities, with additional support of 3 young scientists. Two meetings separated by 9-12 months should be held at ISSI, with additional, self financed technical meetings in-between to coordinate common research efforts.

1 Scientific rationale

1.1 Background

Galactic magnetism is a growing field of research in astrophysics. The crucial role that magnetism plays in the ecosystem of a galaxy has been known for years, but only recently advances in detection methods, technology and computer power have made big leaps forward in understanding galactic magnetic fields possible [1, 2, 3]. As a result, it has become clear that simple models of large-scale galactic magnetic fields following galactic spiral arms are hugely inadequate. Recent data from large multi-wavelength radio-polarimetric surveys have allowed refinement of these models including e.g. anisotropic turbulence and/or vertical field components. However, these models are still data starved and inclusion of magnetic field information through other sources than radio polarimetry is highly desired.

Ultra-high energy cosmic rays (UHECR) reach up to energies of $\sim 10^{11}$ GeV, many orders of magnitude above those achievable by particle accelerators. Both theoretical considerations and also increasing observational evidence points to an extragalactic origin of these particles [4, 5]. Due to interactions with the cosmic microwave background these particles cannot travel far (the well known "GZK effect"), and only very few known astrophysical objects are capable to produce them. Nevertheless, it has not been possible so far to identify the population of UHECR sources, mainly because of the unknown deflections they suffer when traversing the magnetic fields in and around our Galaxy. This uncertainty is owing to (a) the usually very simple models for the GMF used in the UHECR community, and (b) the statistical uncertainty of reconstructing charge and energy of the individual particles from the air showers initiated by them, which are detected in UHECR observatories. Combining the newest insights in Galactic magnetism and the full properties of individual air showers will greatly improve the computed UHECR deflections by the Milky Way magnetic field. But this argument can be reversed: comparing "magnetically corrected" arrival directions of UHECR with probable source scenarios as a function of GMF parameters can provide constraints on GMF models, in particular on larger scales and in the halo of our Galaxy, scales which are difficult to probe by analysing polarized synchrotron radiation or Faraday rotation measures.

Several activities have been pushed forward in the last years to tackle the connection between UHECR and the GMF: Starting with an informal meeting involving both communities in 2009[1],Enßlin and co-workers have developed the Hammurabi Code [6] which allows both to constrain GMF models from astronomical data and to calculate UHECR deflections predicted by these models, and continued the research activity in the subject by developing non-parametric Bayesian methods and software tools [7] to achieve a 3D-tomography of our Galaxy, including its magnetic field [8]. Based on the Hammurabi code and available data from WMAP and pulsar rotation measures, Farrar et al. [1, 9] developed an optimal parametrized model of the Galactic magnetic field, and calculated UHECR deflections in this field to constrain the contribution of the radio galaxy Centaurus A to the UHECR flux. Within a recently awarded Marie-Curie Fellowship, members of our proposed team will collaborate to extend this approach to utilize information in individual air showers on mass and energy of the primary particles.

Given this status of the research field, it is time to undergo a critical review of the applied models and methods by an international distinguished expert team. In particular, it would be important to discuss in which respect the current direction of research, i.e., using improved models of the GMF derive conclusions on UHECR models, can be reversed and to use existing theoretical and experimental knowledge on UHECR origin as a constraint for improved modelling of the GMF. Here is where our project sets in.

1.2 Scientific Goals

With our proposed international team program, we want to achieve the following.

1. Bringing together the leading experts of the field, we want to explore ways for a *Bayesian modelling the GMF, constrained it by existing and future radio data plus UHECR deflections*. We want to critically review the individual approaches in view of magnetic field theory and observations, discuss models of the GMF and how to constrain them by data using parametric or non-parametric Bayesian methods.

2. To include the information contained UHECR air showers into a Bayesian modelling of the GMF we need to develop an UHECR likelihood function. An essential aspect of this is to categorize and parametrize various source scenarios for UHECR, potentially supported by the information contained in multi-messenger indicators like gamma rays and neutrinos. This involves knowledge in both experimental and theoretical aspects of UHECR, as well as in Bayesian GMF modelling, a combination which is uniquely combined in the proposed team.

3. To design and develop a software standard which allows to combine the results of the individual groups (which involves, e.g., standardization of interfaces, data structures, etc.). Such standardized, technical interfaces are proven to accelerate the development of a field as a variety of existing methods become available to a large community, including experimental collaborations harboring large amounts of proprietary data.

By providing this, we expect that our efforts will lead to a better coordinated progress of the understanding of both, the Galactic magnetic Field and the nature and origin of ultra-high-energy cosmic rays.

1.3 Timeliness

Data in all relevant fields will significantly improve in the next years, partially during the period proposed for our program. Planck polarized synchrotron maps will become available in 2014, and will provide higher resolution and accuracy than the currently used maps of the WMAP probe. Low frequency radio observations as performed by LOFAR will explore in particular low-magnetized regions such as galactic halos. LOFAR survey observations of magnetism in the halo of the Milky Way have recently started and are becoming available to this team immediately. Finally, the Pierre Auger Observatory and other UHECR experiments (like the Telescope Array) are about to reach a significant statistics on UHECR events.

Although many of these data are at least temporarily proprietary, our team contains members active in the relevant collaborations. We will therefore exploit the mechanisms to work

[1] *Ultra-high energy cosmic rays and magnetic fields in the Universe*, International Workshop held at Ringberg Castle, Germany, in February 2009, organized by J.P. Rachen, T. Enßlin, and others.

with these data on the basis of collaboration projects or MoUs. Where this is not possible, simulated data can be used for the development of methods and software, to be replaced by real data as soon they become publicly available.

2 Scientific method

Technically, our method is best explained by comparing to Ref. [9], which uses the Hammurabi code to calculate various sets of observables, including UHECR deflection, for a given field model with specified parameters [6]. Bayesian modeling now means, that these parameters are not simply determined by maximizing the likelihood that the model represents some set of observed data, and henceforth apply this model to derive conclusions for UHECR deflections, but to propagate the probability distributions of the field model parameters through various data constraints, which are represented by likelihood functions. Besides such parametric Bayesian approaches there are also non-parametric (or information-field-theory) approaches, as developed by Enßlin et al. [7]. Which approach, or potentially which mixture of them, is most suitable for our purposes will be explored in the initial discussion.

In order to use UHECR as a constraint on the GMF, we need to develop a likelihood function for this constraint. This has never been attempted, because the sources of UHECR, thus their arrival direction outside our Galaxy, are not known. Nevertheless, constructing a UHECR likelihood seems possible when we consider that source scenarios are very limited – only very few classes objects are able to produce them, and these objects are very rare. Moreover, in many production scenarios for UHECR, also PeV neutrinos and GeV-TeV gamma-rays are produced, and as such “multi-messenger indicators” are not affected by magnetic fields, their arrival directions pose additional constraints on source scenarios. Combining all information we have on putative UHECR accelerators, we can then categorize source scenarios and express them in parametrized models. Such production scenarios can then be combined with the information in individual air showers, constraining the charge and energy of each observed particle, with the GMF making the connection between the distributions of particles arriving from extragalactic space to the distributions of properties observed in UHECR experiments. With a significant amount of UHECR data as provided by the Pierre Auger Observatory, this can impose a quite stringent constraint, in particular on the large scale components of the GMF.

Although our team provides all expertise and data access needed to construct the UHECR likelihood function and to apply it within a framework of Bayesian GMF modeling, we expect by the time of the end of our program not more than to be able to demonstrate the viability of the method and to provide first scientific results. In order to keep the results of our work valuable for the future, we therefore want to promote a common software standard, which keeps our methods available for the development future, improved models, constrained by future, improved data sets. In many years, with a largely increased statistics of UHECR events and even better constraints on the GMF from radio-submm data, our work may then still contribute to a common solution of both problems: the structure of the GMF and the origin of UHECR.

3 Expected output

3.1 Individual contributions of team members and collaborations

It is our general policy to respect the proprietary rights of all involved scientists and collaborations in their ideas, developed methods, software tools and data. Therefore, we expect that publications planned in the groups of the individual team members will precede common publications by the team. We will demand, however, that wherever such individual publications have profited form discussions at ISSI, a proper acknowledgement will be included.

3.2 Specific papers and open source code

There are three scientific publications foreseen covering the specific activities in this team

1. A technical paper describing the approach and method to develop a UHECR likelihood function for Bayesian GMF modeling. A relevant part of this will be collection of UHECR source scenario categories and their parametrized representation.

2. A scientific paper presenting the “best GMF” on the base of data available by the end of the project (i.e., mid 2015), including a significant number of high quality UHECR events. We will discuss in this paper the impact of considering UHECR for GMF modeling, but also the consequences for the models of UHECR production in astrophysical sources.

3. A paper and online documentation accompanying our proposed software standard as well as the infrastructure developed in our project, and the relevant data formats and interfaces to use it for future GMF modeling and evaluation of UHECR source scenarios.

In particular for the last paper we expect that it can have a major impact on the future work of both, the UHECR and GMF communities, as such software tools are known to provide a very practical way to mitigate expert knowledge across community borders. This, of course, will also lead to a significant number of citations.

4 Team activity and schedule

4.1 Role of ISSI

Although both GMF and UHECR research are rapidly developing fields and are about to reach a high level of sophistication, and although it is generally understood that they are strongly interdependent, there is still very limited communication between the communities performing research in GMF and in UHECR. The former community consists mostly of radio astronomers, the second of particle physicists. They work in different institutes, publish in different journals, visit different conferences. An important step to generate a common understanding of the mutual achievements and problems in both fields is to bring the leading experts of both communities together to promote the exchange of knowledge and foster common activities.

The set-up provided by ISSI is an ideal environment to achieve this. Especially the possibility to get a dedicated team together twice is optimal for development of our method and software engine. Another important aspect is the maintenance and availability of the ISSI Web page over many years, which can serve as a platform of communication of our software standard, which will give a high visibility to ISSI in both communities.

4.2 Team description and members

Our team consists of a selection of scientists active in theoretical end experimental research on Galactic magnetic fields and UHECR physics (short CVs are attached). All members have indicated their commitment to the project.

- Dr. Torsten Enßlin, Max-Planck Institut für Astrophysik, Garching b. München, Germany
  Planck Collaboration, LOFAR Magnetic Field Key Science Project, Specialist in Bayesian mapping of cosmic magnetic fields
- Prof. Dr. Glennys R. Farrar, New York University
  Pierre Auger Collaboration. Specialist on the UHECR / GMF interaction.
- Dr. Diego Harari, CNEA and CONICET, Argentina
  Pierre Auger Collaboration; Specialist in UHECR point source association
- Dr. Marijke Haverkorn, IMAPP, Radboud University Nijmegen
  LOFAR Magnetic Field Key Science Project; Specialist in observations of Galactic magnetic fields
- Dr. Jörg R. Hörandel, IMAPP, Radboud University Nijmegen
  Pierre Auger Collaboration, LOFAR Cosmic Ray Key Science Project (PI); Specialist on cosmic ray observations
- Dr. Tess Jaffe, Université de Toulouse
  Planck Collaboration; Specialist on Galactic magnetic fields and on the Hammurabi Code
- Prof. Dr. Katarzyna Otmianowska-Mazur, Kraków Jagiellonian University
  Specialist on modeling Galactic magnetic fields
- Dr. Jörg P. Rachen, IMAPP, Radboud University Nijmegen **(Coordinator)**
  Planck Collaboration, LOFAR Cosmic Ray Key Science Project; Specialist in UHECR theory, Bayesian methods and professional software development
- Prof. Dr. Anvar Shukurov, School of Mathematics and Statistics, Newcastle University
  Specialist in physics of magnetic fields
- Prof. Dr. Todor Stanev, Bartol Research Institute, University of Delaware
  IceCube Collaboration, Specialist on all aspects of cosmic rays and air showers
- Dr. Xiaohui Sun, The University of Sydney
  Specialist on modeling of Galactic magnetic fields with the Hammurabi Code
- Dr. Michael Unger, Karlsruhe Institute of Technology (KIT)
  Pierre Auger Collaboration, Specialist on air shower reconstruction

In addition, we propose to involve Prof. Dr. Günter Sigl (Universität Hamburg / DESY, specialist on extragalactic UHECR propagation), and Dr. Andy Strong (Max-Planck-Insitut für extraterristrische Physik, Garching, specialist of cosmic ray propagation in the Galaxy), as self-supported experts. They will not participate in all activities of our team.

4.3 Planned team meetings

We propose to hold two team meetings at ISSI:

In the first meeting, to be held in the Fall/Winter of 2014, we want to get an overview about the status of research in individual groups, the next plans regarding publications of results, and explore options for common activities. We will explicitly discuss suitable approaches to Bayesian GMF modeling and select an approach most suitable for practical applications. We will then start developing methods and approaches for an UHECR likelihood function, and also discuss technical aspects of software packets and how to make them work together.

In a second meeting, to be held 9-12 months later, we will present the results on the UHECR likelihood function and discuss first applications to data. The main goal of this meeting will be to shape and prepare the scientific publication, i.e., the presentation of an optimal GMF model using currently available data, including UHECR constraints. We will also present the software engine in first applications, and collect suggestions for further improvement before public release. We expect release of the final papers within 3 months after the second meeting.

In between, work will proceed at the home institutes of the team members, and we will organize hands-on meeting(s) for part of the team to work together on the development of the software standard and infrastructure (without the need for ISSI support).

4.4 Facilities required

We request to use an ISSI meeting room for the two team meetings, including projection facilities and Internet connection.

4.5 Financial Support requested

We request funding of the local costs for all 12 team members for two one-week meetings in Bern, and travel funding for one person, who will not necessarily be the coordinator. Additionally, we request funding for 3 young scientists to participate in the first, and part of the second meeting.

References

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