Magnetic Helicity estimations in models and observations of the solar magnetic field

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Proposal to ISSI Bern for an International Team in Space Sciences

Abstract

The magnetic environment of Earth is strongly influenced by the Sun and its activity, and it is nowadays recognized to be a highly interlinked system whose variability is known as space weather. The ability to forecast its evolution relies on our understanding of the physical processes that take place on the Sun, such as flares and coronal mass ejections (CMEs). In recent years, magnetic helicity has become an attractive, seemingly viable, and promising candidate for the general description and interpretation of many solar events relevant to space weather. In particular, the conservation properties of helicity under typical solar conditions justifies its use as a tracer during different phases of the life of twisted, tangled magnetic structures, from their formation below the photosphere, to their stability properties in the coronal atmosphere, to their propagation in interplanetary space as ICME. Such a powerful description requires a deep understanding of the properties of magnetic helicity, and accurate methods for its estimation. In spite of the first applications to solar observations already appearing in the literature, no systematic effort has been placed so far in order to assess the reliability of methods for the estimations of magnetic helicity.

The goal of the proposed working group is to redefine the state of the art of existing methods for the estimation of magnetic helicity, based both on photospheric injection, inferred photospheric magnetic connectivity, and volume computations. The comparison between different methods will firstly exploit few numerical test cases that are used in the literature for modeling solar events. This first part of the project is aimed at assessing the accuracy of different methods in a controlled environment. Secondly, we will apply the methods to actual observations, using models of the coronal atmosphere and active regions where necessary (eg., obtained using nonlinear force-free extrapolation). Such a comparison of methods for the estimations of magnetic helicity has never been thoroughly performed yet. By supporting this project, ISSI would therefore provide an unique opportunity for the proposed group of international scientists, who are experts in helicity estimations, to test the practical significance of this physical quantity for space weather predictions.

To this aim, we propose to set up an international team consisting of eight (8) experts representative of the state-of-the-art techniques of magnetic helicity estimations in the solar atmosphere. In a series of three meetings, we plan to compare different methods within a coherent framework using model and observational test cases, and to provide the solar community with thorough and accurate reference works on helicity estimations in solar observations.

Scientific Rationale

The impact of eruptive solar activity is a fast growing issue for a civilization that relies more and more on human-made electrical devices, e.g. satellites, placed farther and farther away from the protective shell of the Earth's magnetic field and atmosphere. Episodically, during solar flares and solar eruptions, the Sun violently ejects large amounts of material which eventually induces geomagnetic storms at Earth. These events may lead to the damage of artificial satellites, disruptions of telecommunications and electrical distribution on Earth, and pose a serious threat to the life of astronauts.

Space weather forecasting, a fast growing discipline of space physics which aims at predicting the level of solar-induced electromagnetic activity in the interplanetary medium, is becoming a necessary element of human exploration and development. However, the quality of the prediction is limited by our incomplete understanding of the basic principles of Sun-Earth connection. As of today, there is no simple criteria, no unique physical quantity that enables the prediction of when and where will a solar flare occur. An intrinsic property of the magnetic field that has been recently proposed as a proxy for the prediction of the violent energy release on the Sun is magnetic helicity.

Magnetic helicity is a quantity that measures the entanglement of the magnetic field, and it is related to the “linking number” of the German mathematician and physical scientist Carl Gauss, which measures the number of times closed curves wind around each other. More generally, magnetic helicity estimates the amount of twist, writhe, and shear of magnetic field lines. Magnetic helicity has the remarkable property of being practically conserved on length- and time-scales of solar relevance (Berger 1984). Therefore, as repeatedly proposed in recent years (see, e.g., Kusano et al. 2002), it could be used as an effective tracer to follow the magnetic field evolution in various evolutionary stages of solar magnetic structures. For instance, when applied to eruptive solar active regions (ARs), the conservation of helicity can in principle be employed to constrain models of flux ropes' evolution, from their formation below the photosphere until their detection as interplanetary coronal mass ejections (ICME).

However, for helicity to be a truly useful quantity for characterizing the magnetic field in different stages of an AR evolution, the significance of its information content in realistic settings must be addressed. In particular, observations can provide only partial information on helicity, an inherent obstacle that hampers a fair assessment of the added value that helicity brings in solar-physics. Therefore, a first open question that needs be addressed is the possibility of using magnetic helicity as a tracer of complex magnetic field evolutions in practical, i.e. solar-relevant, settings.

As the interest in helicity as a key magnetic tracer grows, more methods were recently proposed for its estimation in the solar context. Such methods are divided into three related groups, i.e., those estimating the flux of helicity into the corona from photospheric observations of the magnetic field (yelding an *accumulated helicity,* see, e.g., Pariat et al.

2005; Liu et al. 2012), those directly computing the helicity content of three-dimensional numerical models of the magnetic field (yielding a *volume helicity*, Thalmann et al. 2011; Rudenko & Myshyakov 2011, Valori et al. 2012, Yang et al. 2013), and those measuring helicity through the estimation of the twisting and connectivity of magnetic field lines from magnetic field reconstructions (Georgoulis et al 2012, Guo et al. 2013, Thalmann et al. 2014).

To date, no quantitative comparison between methods has been performed yet, whereas applications to real data from solar cases are already presented to the scientific community. Therefore, it is urgent to assess the reliability of different methods, and to compare their results, both in their principle as well as in their specific implementation. These comparisons need be done firstly within an objective framework, for instance by employing model test cases, and, successively, extending their application to solar observations. Such a focused and systematic effort will provide the reference framework for future developments, and help to understand how to use helicity to trace ARs' evolution in observations. It is only such a systematic effort that can corroborate the use of magnetic helicity in studying fundamental mechanisms of solar eruptions.

Goals and Meeting Plan of the International Team

The general goal of the Team is to asses if and how can helicity be meaningfully used as a tracer of the evolution of the magnetic field in the solar atmosphere, and to properly quantify the reliability of its estimations in practical cases. This requires to understand how the helicity information is modified when the knowledge of the magnetic field is limited to a finite volume or to its values on bounding surfaces, such as the photospheric plane. The answer to this question is likely to be different for different estimation methods (e.g. finite volume vs. flux estimations), as well as dependent on the specific physical setup (e.g. stable vs. unstable evolution). Therefore, an extensive comparison of methods and setups, covering both test cases and observations, is required.

In particular, we plan to compare methods of estimation of the magnetic helicity content in a finite volume. Such techniques will be applied in the first place to test cases representing solar-relevant magnetic configurations. The first test cases that we will consider are two known (semi-) analytical solutions of the force-free equations in three dimensions, described in Low & Lou (1990) and Titov & Démoulin (1989), respectively. In this way, the accuracy of methods for the computation of the volume helicity will be accurately assessed. Similarly, we will consider time-dependent MHD simulations of solar-relevant configurations, specifically chosen to test methods that employ information from the boundary(s) only (but volume methods will be applied as well). Typically, in such MHD simulations a quasi-static phase, in which helicity is injected in the system, is followed by an eruption, which expels helicity from the volume of interest. Examples of such equilibria are described in Pariat et al. 2009, and Aulanier et al. 2013. Such set-ups enable us to study how different helicity estimations techniques describe the change of helicity due to a drastic reconfiguration of the magnetic field, including the susceptibility of each method to the effects of magnetic reconnection. Several such test cases will be prepared in advance of the first meeting.

After having successfully tested and analyzed the performance of the existing methods upon numerical test cases, applications to real observations are envisioned. In this case, in order to employ finite volume methods too, magnetic field extrapolation (Valori et al.

2010, Guo et al. 13, Tahlmann et al. 2014) will be used to model the coronal field. Plenty of observational cases are available, especially exploiting the SDO mission database. The expertise for the coronal field modeling will be provided in the first place by the Team members themselves.

The above scientific program will be covered using three meetings of 4-5 days each, within a 18-20 months period. The programmatic backbone of these meetings is the following:

First meeting, envisioned for September-November 2014

1. Presentations and comparison of existing methods for the computation of helicity, both in finite volumes as well as through fluxes.
2. Test-cases selection, amongst the pool of preselected test cases
3. Strategies for the assessment of the accuracy, speed, reliability of existing codes
4. Preliminary applications of existing codes to test cases (some are fast enough to be applied during the workshop)

Second meeting, to be held about 9 months after the first one

1. Discussion and comparison of results from the application of methods to the numerical test cases
2. Writing tasks for the review paper on helicity estimation methods
3. Progress on methods: challenges and generalizations
4. Selection of observations for applications to real cases.

Third meeting, to be held about 18 months after the first one

1. Application to observations using MHD simulation and/or extrapolations of coronal fields of observed ARs
2. Observational challenges, as opposite to applications to test cases
3. Theoretical challenges: sensitivity to errors
4. Assessment of helicity applicability

The above program will be tuned in the course of the project to optimize the usefulness, concreteness, and productivity of each meeting.

The outcome of the second meeting will be a collective review paper on existing methods and their performances, when applied to test cases. This is expected to become the reference paper for helicity estimations in the solar community. Similarly, the outcome of the third meeting will be an extensive collective article with focus on applications of the methods to observations. In addition, more works are expected to be stimulated by such focused and result-oriented meetings. In the months between the meetings, team members will run their codes on the agreed tests cases, and complete the writing tasks required by the collective articles.

International Team Composition

We propose to assemble an ISSI International Team (with confirmed membership listed in Table 1) to investigate, develop, and evaluate the operational applicability of helicity estimation methods in model and observations. The team members are selected such as to provide the optimal combination of expertise required for the realization of the proposed project. In particular, the team members, besides allowing access to practically all methods known to date for helicity flux and volume computations, are also experts in exploitation of observational data, MHD simulations, and 3D coronal magnetic field reconstruction. In this way, the team will be able to not only to assess the reliability of the available methods, but also to judge the soundness of their results in applications to real observations. Therefore, the team will be able to function in complete autonomy for the completion of the project.

The international level of the team is guaranteed by representatives of seven countries, four of which from ESA Member States.

Table 1: Confirmed members of proposed International Team

Name	Area of expertise	Country
Gherardo Valori (Team Leader)	H in finite volume, Extrapolations	Italy
Etienne Pariat (co-team leader)	H flux, MHD model	France
Yang Guo	H from twist, Extrapolation	China
Yang Liu	H flux, Observations	USA
Manolis Georgoulis	H from twist, Observations	Greece
George Rudenko	H in finite volumes	Russia
Shangbin Yang	H in finite volume, Observations	China
Julia Thalmann	H in finite volumes, Extrapolation	Austria

Added value of ISSI

ISSI provides an unique environment that stimulates collaboration amongst the members of small, strongly focused, and motivated team of experts. On the topic of magnetic helicity we are now at the crucial time in which the availability of a physical concept must be tested for practical applicability to real observations. Such a challenging step is appropriate for a small group of representative experts that can explore all its implications. ISSI provides the perfect setting to achieve the goals proposed here. Additionally, the financial support provided by ISSI aids such progress by offsetting the cost of assembling team members in a common location, who (for the team proposed here) would otherwise be dispersed across several countries. The application is to ISSI-Bern as the more practical location given the countries of residence of the team members (see Table 1).

Required support

The proposed eight-member International Team will meet over three meetings lasting 4-5 days each, over a 18-20 months period. In addition to the core members of the team, few self-supported experts and young scientists are expected to take part in the meetings. For the meetings, the International Team will require a meeting room for about 10–12 people, with projection equipment and internet connectivity. We request the standard financial support of the team members' local expenses. We intend to profit from the Young Scientist scheme, with beneficiaries to be identified upon approval of this proposal. Depending on the application outcome, we would reserve to decide at a later stage if the travel expenses of the team leader should be rather devolved to a different team member. Publication charges of the resulting journal articles will be covered by the home institutions of the team leadership. High-performance computing facilities will be provided by the home institutions of the team members.

Annex 1 : References

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