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Recent progresses in the use of 3D MHD simulations for solar irradiance reconstructions

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Abstract. The use of 3D magneto-hydrodynamic simulations of the solar atmosphere in modeling irradiance variations seems a natural evolution of the current irradiance reconstruction techniques making use of one-dimensional, static, atmosphere models. Nevertheless, the development of such new models poses serious computational challenges. This contribution focuses on recent progresses made in the development of novel irradiance reconstruction models making use of 3D MHD simulations and discusses current and future challenges.

1. Introduction

Variations of solar and stellar irradiance affect the atmosphere and climate of the Earth and exo-planets. Moreover, understanding solar variability provides useful insight in modeling stellar magnetic variability, which in turn, is of paramount importance for improving the detection of exo-planets and for characterizing the habitability zones of stars (Fabbian *et al.* 2017). Measurements of solar irradiance variations are intermittent, dis-homogeneous, and often affected by instrumental calibration and degradation effects. Moreover, systematic measurements started only in the late seventies. Time series of irradiance variations necessary to assess the influence of irradiance variations on the Earth atmosphere are therefore complemented and extended in time with irradiance estimates obtained by reconstructions. Unfortunately, even reconstructions present disagreements that do not allow to correctly assess the influence of solar irradiance variability on the Earth atmosphere (Ermolli *et al.* 2013). This contribution focuses on recent progresses in developing novel irradiance reconstruction techniques based on the use of three dimensional magneto-hydrodynamic (3D-MHD) simulations of the solar atmosphere, which we expect to greatly improve reconstruction techniques based on semi-empirical approach.

Semi-empirical irradiance reconstructions are performed by combining measures of the variation of surface magnetism, as derived by the analysis of full-disk data, with estimates of the radiative emission synthesized with atmosphere models. These reconstruction techniques have been proven successful in reproducing more than 90% of the variability of the measured Total Solar Irradiance (TSI, i.e. the irradiance integrated over the whole spectrum), but the agreement is less good when studying timescales longer than one decade and/or restricting the analysis to finite spectral ranges. Among the different aspects that may contribute to explain such uncertainties, the employed synthetic spectra are a point of concern. Synthesis of stellar spectra strongly depend on the assumptions adopted for the radiative transfer calculations as well as on the employed atmosphere models. Concerning this last aspect, irradiance reconstructions have relied so far on the use of semi-empirical one-dimensional static atmosphere models, which have been most typically derived to reproduce measured disk-integrated spectra (e.g. Fontenla, Avrett & Loeser 1993). By their nature, such atmosphere models cannot capture the fine spatial and temporal scales of features observed with modern high spatial resolution instrumentation, and more in general the complex three-dimensional nature of the processes that describe the propagation of radiation through convective magnetized plasma. More specifically, the use of one-dimensional static atmosphere models present the following drawbacks: 1) May fail in reproducing irradiance variability at spectral and temporal scales other than those employed to derive the models; 2) May fail in reproducing observed properties of quiet and magnetic structures; 3) Radiative transfer codes other than the ones used to derive the atmosphere models may produce different spectra; 4) Can be hardly validated with independent measurements of properties of quiet and magnetic plasma (as for instance doppler or spectro-polarimetric measurements).

2. Use of 3D-MHD models for solar irradiance reconstructions

Uitenbroek & Criscuoli (2011) employed 3D MHD simulations of the solar photosphere to show that semi-empirical one-dimensional models do not describe the physical average properties of the solar atmosphere, thus explaining the issues 1) and 2) listed above. The use of 3D MHD simulations of the solar photosphere and chromosphere for irradiance reconstructions is in this respect a huge step forward, as they are derived solving basic magneto-hydrodynamic equations with a few observational constraints (Stein 2012, Nurdlund, Stein & Asplund 2009). These simulations, which typically represent small areas of the solar atmosphere (a few square-arcsec horizontally, and vertically a few Mm above and below the optical depth unity surface; *box-in-a-star* regime) with high spatial resolution (a few tens of kilometers or better), have been proven to reproduce the observed properties of the solar spectrum with a higher degree of accuracy than one-dimensional models (e.g. Asplund *et al.* 2009; Pereira *et al.* 2013).

The use of these simulations for irradiance reconstruction purposes has been for long hampered by the highly demanding resources required for both the atmosphere modeling and the radiative output computations. First applications have been therefore limited to investigations of the radiative properties of magnetic structures (e.g. Tritschler & Uitenbroek 2006; Afram *et al.* 2011, Criscuoli 2013; Thaler & Spruit 2014; Criscuoli & Uitenbroek 2014a) or to qualitative estimates of irradiance variability (Criscuoli & Uitenbroek 2014b). The crescent availability of supercomputers has recently allowed to overcome computational difficulties, at least for what concerns simulations of the solar photosphere and spectral synthesis performed under Local Thermodynamic Equilibrium (LTE). Nowadays, time series of solar and stellar photospheres obtained at different level of magnetization produced with different MHD codes are available under request or at specific databases (e.g. Beeck *et al.* 2013; Rempel 2014; Kitiashvili *et al.* 2015; Salhab *et al.* 2018). Computations of the whole spectrum at the spectral resolution necessary to model the observed variability (1 nm or better) is possible making use of pre-computed tables of opacities (e.g. Norris *et al.* 2017). Thanks to such advancements, Shapiro *et al.* 2017 recently estimated the contribution of granulation to high frequency (minutes to hours) TSI variations using 3D hydrodynamic simulations. The first reconstruction of TSI irradiance variations making use of 3D-MHD simulations was presented in Yeo *et al.* 2017. These reconstructions combine photospheric magnetograms acquired with the Helioseismic and Magnetic Imager (HMI) with spectra synthetized with photospheric simulations obtained with the Max Planck Institute for Solar System Research/University of Chicago Radiation Magneto-hydrodynamics (MURaM, Vögler *et al.* 2005) code. The agreement between the synthetic and observed TSI variations is at 95% level, which is comparable with the agreement obtained with other models.

3. Future challenges

The major challenge we are currently facing is the use of MHD simulations to model and reconstruct the irradiance in the UV. Most of the radiation at these spectral ranges originate in the chromosphere, which is a layer of the atmosphere that is extremely difficult to model for both what concerns the correct description of the physical processes involved and the computational resources required (e.g. Freytag *et al.* 2012). At the moment, Bifrost (Gudiksen *et al.* 2011) is the most advanced code for reproducing the properties of the solar chromosphere. Nevertheless, recent studies indicate that synthetic spectra obtained with Bifrost snapshots fail in fully capturing observed properties of the chromosphere (e.g. Bastian *et al.* 2017), thus suggesting that the Bifrost code still does not properly take into account physical processes occurring in the higher layers of the solar atmosphere. Furthermore, the production of statistically significant time series of snapshots to use for irradiance reconstruction as well as non-LTE radiative transfer computations are still prohibitive. Given the great interest shown by the solar community in recent years for both modeling the chromosphere and improving multi-dimensional non-LTE radiative transfer codes (e. g. Sukhorukov & Leenaarts 2017), together with the rapid increase in the computational power, these issues will be likely overcome in the next future.

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