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Advancing Radio Diagnostics of Space Weather Plasma Processes

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Abstract

Space Weather perturbations are originated by a variety of plasma processes, whose signatures are observable in the radio spectrum. The interpretation of these signatures to infer the physics at the sources is a fundamental requirement in developing Space Weather science and operation models. Hence, the advancement both of radio observation techniques and radio emission and propagation modelling is a must. A step to achieve this goal cannot be separated from the availability of a collaborative approach for data and model sharing and reviewing.

1. Introduction

The physical state of coupled plasma environments and its short- and long-term time evolution in the Heliosphere, on the Sun, in the Interplanetary Medium, in the Magnetosphere, and in the Geospace, are named, respectively Weather and Climate (Figure 1). In particular, we can further specialise the terminology referred to sub-domains such as, e.g., the Solar Radio Weather, which describe the short-term radio emissions by the Sun.

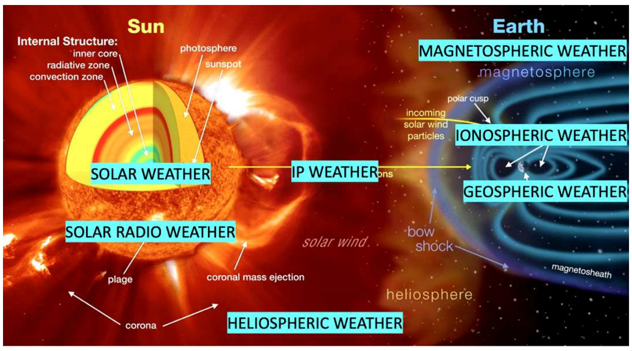

Figure 1. Coupled plasma domains in the Heliosphere and Sun-Earth system and related Space Weather and Climate. (Credit: NASA, M. Messerotti)

Figure 2 depicts with a higher level of detail the particle and photon signatures of Heliospheric and Solar Weather, which determine Interplanetary, Magnetospheric, Ionospheric, and Geospheric Weather at the Earth. It comes immediately evident that a comprehensive knowledge of Space Weather plasma processes, their coupling and signatures is needed to understand the interactions and the relevant impacts on the target physical systems in space and on the ground at the Earth, and to develop operation models capable to predict their timing and strength in advance to allow mitigation actions.

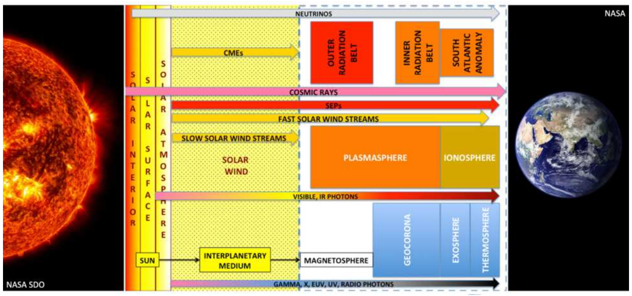

Figure 2. Space Weather particle and photon signatures in the Sun-Earth environment [1].

2. Heliospheric Weather and Climate

The Heliospheric Weather and Climate (Figure 3) are characterised by the inner forcing and the outer forcing physical agents related to the Sun and its activity features and to the stars located in the solar neighbourhood respectively [2].

The inner forcing includes Solar Energetic Particles (SEPs) accelerated by solar energetic processes in the keV-GeV energy range and propagating as streams in the Interplanetary Medium, Fast and Slow Solar Wind Streams accelerated in Coronal Holes and Coronal Streamers, respectively, and Coronal Mass Ejections (CMEs) accelerated by flaring processes and prominence eruptions. The interaction of plasmas at different speed and density originates shocks and large-scale plasma structures in the Interplanetary Space like Shock Interaction Regions (SIRs) and Corotating Interaction Regions (CIRs).

The outer forcing is due the fact that the Heliospheric plasma is confined by the Interstellar Wind plasmas, which are magnetised as they carry the magnetic fields of the stars that originate them, just as the Solar Wind plasma transports the Sun's magnetic field anchored to the Sun. Furthermore, it is penetrated by Interstellar Neutrals, Gamma Ray Bursts (GRB) and Cosmic Rays in the GeV-EeV energy range from galactic and extra-galactic high-energy sources.

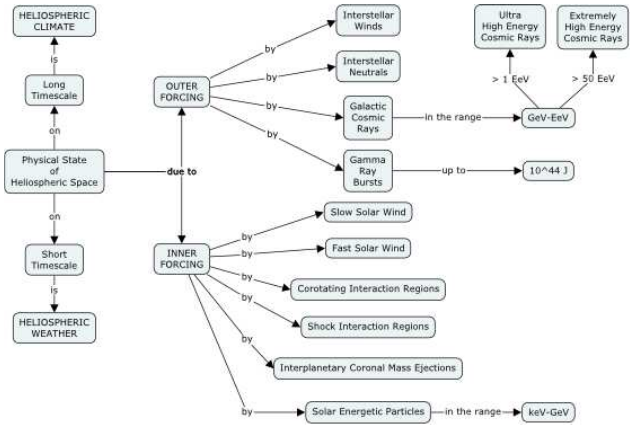

Figure 3. Synopsis of Heliospheric Weather and Climate inner and outer forcing [2].

3. Solar Weather and Climate

Space Weather perturbations in the Heliosphere are mainly originated by the Sun, whose physical state characterises Solar Climate and Solar Weather [2] (Figure 4).

Inner forcing is determined by the physical properties and large-scale plasma processes of the Sun as a star. In fact, their spatial and time evolution and interplay concur to determine the solar activity level, i.e., the formation of localised magnetic fields in active regions, which are unstable and can impulsively release the stored magnetic energy as plasma heating, particle acceleration, and magnetised plasmoid ejection. The evolution of the Sun as a star plays a role on Solar Climate, whereas the generation of a dipolar magnetic field by dynamo mechanisms, the change of dipolar magnetic field into toroidal ones by solar rotation, and the erosion of toroidal fields by meridian plasma flows, originate and modulate the solar activity cycle, which is relevant to Solar Weather.

The outer forcing consists of the solar activity features, which, upon instability, produce a varied set of small- and large-scale plasma emissions. Among the large number of solar activity features, at small spatial scales we mention sunspot groups, where magnetic reconnection processes during flares produce electromagnetic outbursts, SEPs, and CMEs. At large spatial scales, erupting prominences originate CMEs, Coronal Holes, and Coronal Streamers accelerate Solar Wind plasma with different features, which interact in the Interplanetary Medium originating shocks among interplanetary regions as CIRs and SIRs.

Thermal and non-thermal, incoherent and coherent radio emissions [5, 6, 7] are the information carriers of plasma heating and interactions among accelerated particle beams on a microscopic spatial scale and particle streams on a macroscopic spatial scales and magnetised background plasmas like the Solar Wind. Furthermore, particle beams can be accelerated at plasma regions' shock fronts under various physical conditions, and the related radio emissions represent effective diagnostics for the emitting plasma environments [8].

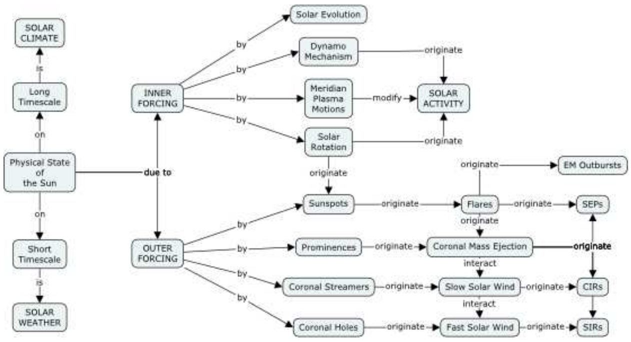

Figure 4. Synopsis of Solar Weather and Climate inner and outer forcing [2].

4. Heliospheric Radio Emission Sources

The complexity of the phenomenological scenario relevant to heliospheric radio emission sources and the variety of typologies of related radio signatures is concisely schematised in Figure 5 [3].

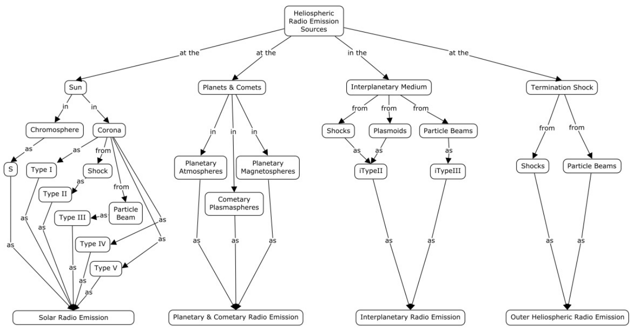

Figure 5. Synopsis of heliospheric radio emissions as tracers of plasma processes [3].

Heliospheric radio sources can be divided into four main categories based on the body/physical system where they are formed and located with the respective exciting agents, i.e.

1. Sun (Chromosphere and Corona);
2. Planets (Atmosphere);
3. Comets (Plasmasphere);
4. Interplanetary Medium (Shocks, Plasmoids, Particle Beams);
5. Outer Heliosphere/Termination Shock (Shocks, Particle Beams).

Radio emissions from the listed plasma environments have been observed [9], classified, and modelled based both on the available knowledge on radio emission processes in plasmas and on measured/inferred plasma and magnetic field parameters at the source and along the radio propagation path.

Hence, in principle, the radio emission source formation, structure, and evolution can be inferred from the observed radio emissions by reverse modelling. Similarly, the plasma structure at the source and along the propagation path can be inferred from the radio observations.

Hence, in addition to radio physics models, radio emissions can be used as precursors/proxies of Space Weather events and as inputs to the forecasting models in Space Weather operations after model validation.

5. Solar and Interplanetary Radio Diagnostics

To illustrate the use of radio emissions to diagnose physical processes at the source, we consider the synopsis of solar and interplanetary radio diagnostics reported in Figure 6 [4].

Solar continuous radio emission (S-component) is indicative of the presence of solar active regions, i.e., of the level of solar activity.

Solar Noise Storms are connected with the rearrangement of magnetic fields in the Corona.

Low-frequency-drift Type II radio bursts are produced by propagating hydrodynamic shocks in the Chromosphere and Corona like, e.g., the shock front of CMEs, whereas high-frequency-drift Type III radio bursts are the radio signature of beam-plasma interactions in flaring regions, and radio Spikes at high frequency are originated during the impulsive phase of solar flares when electrons are accelerated at high energies, so that they are proxies of the fragmentation of energy release in Chromosphere and Corona.

Similarly, interplanetary Type II radio bursts are originated by hydrodynamic shocks propagating in the Interplanetary Medium, and interplanetary Type III radio bursts are the signature of accelerated beam-interplanetary background plasma interactions.

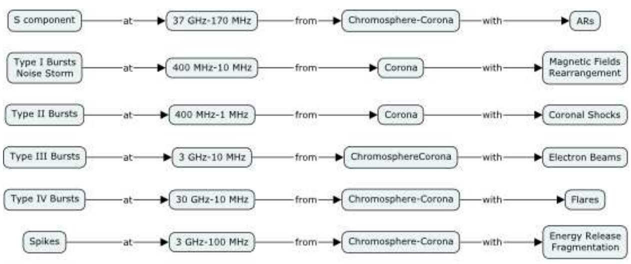

Figure 6. Synopsis of solar and interplanetary radio emissions [4].

An effective reverse modelling must rely on a consistent physical model of the propagation medium and the source, but, as an example, this is quite difficult to achieve in the case of the solar corona, because, to date, the coronal magnetic field can only be inferred and not reliably measured in situ, and Semi-empirical models are used.

This aspect heavily affects any reverse modelling and the use of radio signatures in forecasting, e.g., flare occurrence and Space Weather perturbation triggering.

6. Requirements for Advancement in the Field

As pointed out in the previous sections, the successful use of radio diagnostics in Space Weather operations requires the availability of the following conceptual and applicative tools [10, 11]:

a. Comprehensive spectropolarimetric radio observations with adequate time, frequency, and spatial coverage;
b. Identification of radio precursors to perturbative phenomena;
c. Effective data fusion tools to exploit the data information content via an associative approach;
d. Comprehensive physical models of radio source formation and evolution;
e. Consistent physical models of radio emission processes and radio wave propagation;
f. Effective data and model assimilation tools to optimally combine theory and observations;
g. Validated operational models to forecast Space Weather perturbative events based on radio events.

Many radio data sets are available, but are not accessible through a unified interface capable to relieve the user from the burden of fragmented data search.

A wealth of radio science models exists in the literature, but is not organised in a way to be flawlessly searched by the user nor reviewed in the framework of their applicability in the Space Weather framework.

When considering the above, data fusion and model assimilation (Figure 7), which are key steps in Space Weather Research to Operation (R2O) are far from being carried out. In fact, this transition process requires the availability of adequate archiving facilities to access data and models and to analyse them in a structured way.

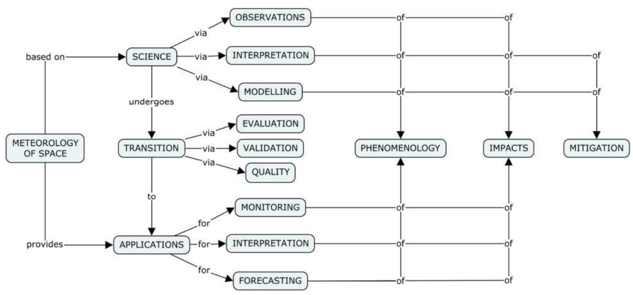

Figure 7. A general workflow for the Research to Operation transition in the field of Meteorology of Space (Space Weather and Space Climate).

Similar considerations hold for the identification of radio precursors, which could greatly benefit from Deep Learning techniques applied to well-structured radio data sets.

In this context, a quantum leap would be provided by a collaborative work to set up: 1. an archive of existing radio science models, reviewed and tagged in the light of Space Weather applications; 2. an archive of radio data, searchable via a unified interface in an user-transparent mode.

These assets are a must to enable the advancement to data fusion and model assimilation as well as to knowledge discovery in data bases [12, 13], capable to lead to the tool g. in the above list, i.e., validated operational models to forecast Space Weather perturbative events based on radio events. In fact, this is the most relevant need in Space Weather operations, which would greatly benefit from the parameters derived from radio physics observations and modelling in a way that has not been comprehensively done to date.

7. Acknowledgements

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References

[1] M. Messerotti, " Degraded Environments By Extreme SWx Events: How to Cope With in Military Operations?" CMDR COE Annual Conference 2021, Sofia, online meeting https://www.cmdrcoe.org/menu.php?m_id=40&c_id=88.

[2] M. Messerotti, "Defining and Characterising Heliospheric Weather and Climate," in Space Weather of the Heliosphere: Processes and Forecasts, Proc. of the International Astronomical Union, IAU Symposium, **335**, 2018, pp. 226-231, doi: 10.1017/S1743921317008857.

[3] M. Messerotti, "Radio Emission Processes as Tracers of Heliospheric Weather: An Ontological Approach," in The Sun, the Solar Wind, and the Heliosphere, M.P. Miralles and J. Sanchez Almeida (Eds.), IAGA Special Sopron Book Series, 4, pp. 209–219, Berlin: Springer, 2011, ISBN:978-90-481-9786-6.

[4] M. Messerotti, "Radio science for space weather," 2016 URSI Asia-Pacific Radio Science Conference (URSI AP-RASC), 2016, pp. 459-462, doi: 10.1109/URSIAP-RASC.2016.7601367.

[5] G. A. Dulk, "Radio emission from the sun and stars," Ann. Rev. Astron. Astrophys., **23**, 2016, pp. 169–224, doi: 10.1146/annurev.aa.23.090185.001125.

[6] A. O. Benz, "Plasma astrophysics: kinetic processes in solar and stellar corona," Astrophysics and Space Science Library, **184**, Dordrecht: Kluwer, 1993, doi:10.1007/978-94-011-2064-7.

[7] T. S. Bastian, A.O. Benz, and D.E. Gary, "Radio emission from solar flares," Ann. Rev. Astron. Astrophys., **36**, 1998, pp. 131–188, doi:10.1146/annurev.astro.36.1.131.

[8] M. Messerotti, "Solar Radio Spectrography: Comprehensive Diagnostics for Space Weather Applications," 2018 2nd URSI Atlantic Radio Science Meeting (AT-RASC), 2018, pp. 1-4, doi: 10.23919/URSI-AT-RASC.2018.8471360.

[9] M. Messerotti, "Radio Observations for Space Weather," 2019 URSI Asia-Pacific Radio Science Conference (AP-RASC), 2019, pp. 1-4, doi: 10.23919/URSIAP-RASC.2019.8738750.

[10] H. Opgenoorth, et al., "Assessment and recommendations for a consolidated European approach to space weather - as part of a global space weather effort," *Journal of Space Weather and Space Climate*, **9**, id. A37, 2019, 9 pp., doi: 10.1051/swsc/2019033.

[11] C. Plainaki, et al., "Current state and perspectives of Space Weather science in Italy," *Journal of Space Weather and Space Climate*, **10**, id. 6, 2020, 51 pp., doi: 10.1051/swsc/2020003.

[12] D. Pérez-Suárez, et al., "HELIO - Discovering solar effects in all the heliosphere," European Planetary Science Congress 2013, held 8-13 September in London, UK. Online at: http://meetings.copernicus.org/epsc2013, id. EPSC2013-328.

[13] R. Bentley et al., "HELIO: Discovery and Analysis of Data in Heliophysics," 2011 IEEE Seventh International Conference on eScience, 2011, pp. 248-255, doi: 10.1109/eScience.2011.42.