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The Plasma Universe: A Coherent Science Theme for Voyage 2050

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In review of the White Papers from the Voyage 2050 process[1] and after the public presentation of a number of these papers in October 2019 in Madrid, we as White Paper lead authors have identified a coherent science theme that transcends the divisions around which the Topical Teams are structured. This note aims to highlight this synergistic science theme and to make the Topical Teams and the Voyage 2050 Senior Committee aware of the wide importance of these topics and the broad support that they have across the worldwide science community.

Keywords: plasma, space physics, astrophysics, european space agency—ESA, voyage 2050

Baryonic matter in the Universe is almost exclusively in the plasma state. It forms structures on a huge range of scales, reaching from the kinetic electron and ion microscales to the size of the entire observable Universe. These plasmas include very diverse objects such as magnetic cavities around comets, planetary magnetospheres, the solar atmosphere, the outer heliosphere, accretion discs around compact objects, galaxy-scale "Fermi bubbles," the intracluster medium, and the intergalactic medium permeating the cosmic web. The key difficulty in understanding of all these objects lies in the two-way nature of the intrinsic multi-scale physics of plasmas: processes on the largest scales affect the small-scale physics, and processes on the smallest scales affect the large-scale evolution of plasmas.

[1]All Voyage 2050 White Papers are available online at https://www.cosmos.esa.int/web/voyage-2050/white-papers.

These multi-scale processes are united by *fundamental physics questions* that underpin the physics addressed in all of the 18 White Papers referenced below, e.g.

• How are electrons and ions heated and accelerated, and how is energy partitioned?
• What is the role of the magnetic field?
• What are the properties and roles of different energisation regions in plasma structures?
• What is the role of plasma physics in the formation and evolution of different processes and objects including flux tubes, turbulence, waves, flows, jets, discs, magnetospheres, coronae, and halos?
• What are the effects of rapid and discontinuous processes such as shocks and reconnection?

The answers to these *fundamental questions* are very important for a wide range of processes in the Universe including:

• accretion of matter onto compact objects,
• cosmic-ray acceleration,
• galaxy formation,
• heat and energy transfer, conduction, diffusion, and turbulence in plasma flows on all scales, in intergalactic, interstellar, and interplanetary media,
• magnetic-field generation through dynamo processes,
• magnetospheric dynamics,
• stellar activity and coronal dynamics, and
• space weather.

We have specifically identified four fields of study in the proposed Voyage 2050 White Papers that are linked by this common theme:

Astronomy from the UV to soft and hard X-ray wavelengths is a powerful tool to explore different parameter regimes and examples of plasma environments on large scales based on a whole-system overview. They allow us to identify plasma shocks, thermal processes in accretion flows onto compact objects such as neutron stars and black holes, the large-scale geometry of matter, and even elemental and charge-state composition through the effective use of spectroscopy and polarimetry [Lebouteiller et al., 2019; Frontera et al., 2021; Guidorzi et al., 2021; Nicastro et al., 2021; Simionescu et al., 2021; Soffitta et al., 2021; Uttley et al., 2021].

Solar physics investigates processes on intermediate scales and links the physics explored by X-ray and UV astronomy to the local environment of the solar system. It allows us to obtain detailed spectroscopic imagery of plasma phenomena that we can interpret directly (Branduardi-Raymont et al., 2021; Erdélyi et al., 2021; Matthews et al., 2021; Peter et al., 2021).

Heliospheric, magnetospheric, and cometary physics studies of *in-situ* plasma phenomena such as the acceleration and heating of particles can be directly linked to larger structures with a good level of system-wide imagery and context (McCrea et al., 2019; Branduardi-Raymont et al., 2021; Erdélyi et al., 2021; Götz et al., 2021; Matthews et al., 2021; Peter et al., 2021; Rae et al., 2021; Roussos et al., 2021; Wimmer-Schweingruber et al., 2021).

In-situ plasma physics explores the near-Earth plasma environment (e.g., pristine and shocked solar wind, bow shock, and magnetosphere) and the plasma environment around other solar-system objects. It allows us to analyse the detailed fundamental interactions and the micro-scale processes that determine the large-scale evolution and thermodynamics of matter (Branduardi-Raymont et al., 2021; Götz et al., 2021; Rae et al., 2021; Retinò et al., 2021; Verscharen et al., 2021; Wimmer-Schweingruber et al., 2021).

Although these science topics appear quite diverse and each White Paper is being evaluated on its own merit by their respective Topical Team, we emphasise that all of them will mutually benefit from each other. For instance, the interpretation of X-ray and UV observations, reaching from compact objects to the largest structures in the Universe, depends on a solid understanding of fundamental *in-situ* plasma physics. On the other hand, the *in-situ* plasma community will benefit from cross-disciplinary collaboration with plasma astrophysicists by studying a much wider range of plasma conditions, some of which cannot be studied *in situ*. The same benefit applies likewise to the solar, heliospheric, magnetospheric, and cometary fields. Moreover, numerical modelling of plasmas in different regimes with shared physical understanding will underpin much of the developments in these fields.

The synopsis above and the related Voyage 2050 White Papers show that a common and coherent science theme has emerged from the Voyage 2050 process. This theme is linked by the common interest across large parts of the ESA-science community in exploring structures in the Universe that are shaped by plasma processes across a large variety of scales. This science theme spans across all of the installed Topical Teams. We are convinced that the adoption of this coherent science theme by ESA through a programme of missions addressing plasma physics in its many forms will make transformative advances in our knowledge of fundamental plasma physics questions and of a wide range of processes that are of greatest importance for our understanding of the Universe.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors contributed to the writing of this article.

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