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Jupiter Radiation Belts (Heliophysics 2024 Decadal Whitepaper Team); Kollmann, Peter; Allanson, O.; Arruda, L.; Berland, G.; Blum, L. W.; Bortnik, J.; Cao, X.; Chen, T. Y.; Clark, G.; Cohen, I.; Cooper, J. F.; Crary, F.; Desai, R. T.; Dialynas, K.; Drozdov, A.; Dudnik, O. V.; Dunn, W. R.; Hospodarsky, G. B.; Huybrighs, H.

DOI:
10.3847/25c2cfeb.6eb85c6e

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Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):
Jupiter Radiation Belts (Heliophysics 2024 Decadal Whitepaper Team), Kollmann, P, Allanson, O, Arruda, L, Berland, G, Blum, LW, Bortnik, J, Cao, X, Chen, TY, Clark, G, Cohen, I, Cooper, JF, Crary, F, Desai, RT, Dialynas, K, Drozdov, A, Dudnik, OV, Dunn, WR, Hospodarsky, GB, Huybrighs, H, Jackman, CM, Jaynes, AN, Jun, I, Khurana, KK, Kraft, R, Kronberg, EA, Lejosne, S, Li, W, Li, X, Liuzzo, L, Ma, Q, Marshall, R, Mauk, B, Nénon, Q, Nordheim, TA, Paranicas, C, Plainaki, CC, Regoli, LH, Roussos, E, Shprits, Y, Siecard, A, Simon, S, Smith, HT, Sorathia, K, Spence, HE, Sulaiman, A, Sun, Y, Tu, W, Turner, DL, Usanova, ME, Williams, P, Yuan, C-J & Wu, X 2023, 'Jupiter’s radiation belts as a target for NASA’s Heliophysics Division: Whitepaper #215 in the Decadal Survey for Solar and Space Physics (Heliophysics) 2024-2033.', *Bulletin of the American Astronomical Society*, vol. 55, no. 3, pp. 1-10. https://doi.org/10.3847/25c2cfeb.6eb85c6e

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Jupiter’s radiation belts as a target for NASA’s Heliophysics Division

A White Paper for the 2024-2033 Solar and Space Physics (Heliophysics) Decadal Survey

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Synopsis

NASA’s Heliophysics division studies “the Sun, the heliosphere, and Earth’s magnetosphere and... universal plasma phenomena”. We argue that Jupiter's radiation belts, magnetosphere, and near-space environment should be considered as relevant targets for NASA’s Heliophysics missions. All universal processes called out in the previous Decadal study can be found around Jupiter. Such physics is much more relevant and directly maps to the defined focus of NASA’s Heliophysics division than to the core sciences of NASA’s Planetary Sciences division.

Jupiter’s magnetosphere is an environment of extremes: of all the planets in the solar system it is the **largest natural particle accelerator**, has the strongest magnetic field, the fastest spin, and the most geologically active moon that provides plasma to the magnetosphere. While the intensities of ultrarelativistic electrons with energies in excess of several MeV at Earth become significant only during the most rare and extreme events, electron acceleration to many tens of MeV occurs at Jupiter all the time. Even relativistic heavy ions such as oxygen and sulfur can be trapped up to tens of GeV. All this makes Jupiter ideal to particularly **study the fundamentals of particle acceleration**. At the same time, it also provides a unique opportunity to study the potential extremes of terrestrial space weather.

While the waves driving acceleration processes at Earth are found throughout the L-shells of the radiation belts, at Jupiter they are limited to more discrete and narrow ranges, making it easier to disentangle local from non-local acceleration. While energetic particle dynamics at Earth’s magnetosphere are in part driven by magnetopause shadowing and substorms, Jupiter’s belts are embedded so deep within the magnetosphere that these effects are thought to be negligible: the outer magnetosphere is instead a huge reservoir for pre-accelerating radiation belt particles. The heavy ions released from the moons provide ample opportunity to

distinguish mass- and charge-dependent acceleration processes. Jupiter is therefore in many ways **a very well controlled laboratory** to study space physics processes, particularly extreme particle acceleration, that occur also at the Earth and in the rest of the universe.

In addition, Jupiter is a stepping stone to extrasolar objects such as pulsar nebulae or magnetized stars. While the high energy components around such objects are otherwise only accessible through their X-ray and radio emissions, Jupiter is the only planet where we can observe the same emissions and at the same time establish a "ground truth" through in-situ measurements.

Preface

Energetic particles are ubiquitous throughout the universe, yet the mechanisms and their interactions through which **nature accelerates charged particles to near-lightspeed** are yet to be understood. Jupiter's radiation belts are an ideal environment to study particle acceleration because the energies of the charged particles trapped in its magnetic field go beyond what is found at the Earth and reach as close as we can within our Solar System to the extreme energies found around extrasolar objects such as supernovae remnants or various magnetized stars (Mauk+12). At the same time, Jupiter is, different to astrophysical targets, accessible with spacecraft that allow both in-situ and remote measurements. **Jupiter therefore links acceleration in the terrestrial magnetosphere and astrophysical settings.**

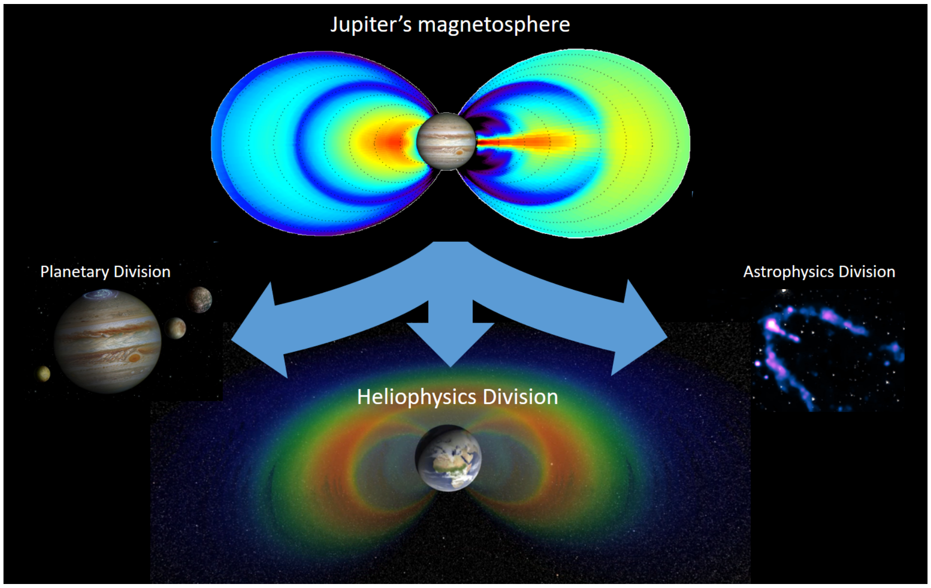


Fig. 1: The space physics environment at Jupiter has relevance to NASA's Planetary Science, and Astrophysics Divisions, but is most relevant to the Heliophysics Division. Image credits: Nenon+17,18 JGR, NASA, CXC, STScI, JPL-Caltech, GSFC.

Jupiter has traditionally been a target of NASA's Planetary division. Yet their focus is shifting towards solar system origins, structure and dynamics of various worlds, and life (National Academies+22). Space physics for them is increasingly considered as a tool to support other science areas, for example to understand the weathering of planetary surfaces. It will be up to NASA's Heliophysics division to study space physics for its own sake.

The Heliophysics division has never been restricted to the heliosphere. One of the key science goals of the previous 2013 Decadal Strategy for Solar and Space Physics was to "Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe" (National Academies+13). Jupiter, particularly its radiation belts, are an ideal "cosmic laboratory for studying universal plasma phenomena". We will argue here that its radiation belts are of broad relevance to Heliophysics and that they should therefore be treated as valid targets that deserve focused investigations from NASA's Heliophysics Division (see Fig. 1). Companion White Papers discuss a possible implementation into the COMPASS mission to Jupiter (Clark+22) and the science of Jupiter's magnetosphere in general (Crary+22).

A new perspective on Earth's processes

Another key science goal for Heliophysics is to "determine the dynamics and coupling of Earth's magnetosphere" with a "priority [of] understanding charged-particle acceleration, scattering, and loss" (National Academies+13). Comparative magnetosphere studies are a powerful tool to understand these processes and test hypotheses that were largely developed based on the terrestrial case. **By observing other planets we can do the practical experiment in reality, not just in a simulation, of tuning parameters** (wave intensities, magnetic field strength, etc.) to quantify their relative contributions and to test if our theories hold.

Originally, acceleration in the terrestrial radiation belts was thought to be mostly driven by adiabatic transport (Schulz+74). The potential of local acceleration was recognized much later (Horne+98). Acceleration is a multifaceted, stepwise process. Because of the complex interplay between the competing processes, their relative importance at Earth is still under active investigation, both in the big picture as well as for single events (e.g. Shprits+13 Nat.Phys. vs. Mann+16 Nat.Phys.).

Jupiter's environment offers a new perspective on particle acceleration and **may be better suited than Earth's to disentangle different processes** because some complications do not exist: While Earth's outer belt comes and goes (e.g. Reeves+15) in response to magnetopause shadowing and substorms, Jupiter's radiation belts are so deeply embedded in the giant magnetosphere that its belts are relatively stable by comparison (Kollmann+18). While local acceleration at the Earth can occur throughout the L-shells of the radiation belts (e.g. Aryan+21), local acceleration at Jupiter (e.g. Woodfield+14) is limited to the relatively narrow region around its mass loading moons, while everywhere else it was suggested that acceleration conserving the first two adiabatic invariants is dominating (see Fig. 2).

A giant magnetosphere may therefore be a simpler system in some aspects compared to Earth's relatively small and heavily mixed system. Not having to consider the distinction between local acceleration and adiabatic transport, makes it more straightforward to focus on the details within these two classes of processes: What actually drives radial transport (global electric fields, interchange of some kind, ULF waves, turbulence in the ionosphere, etc.) and how local acceleration evolves (how are waves triggered, what is the impact of different waves under different conditions, are particle and wave intensities self-limiting), to just name a few. Our current knowledge suggests that at Jupiter we will be able to set aside some of Earth's complications. We will need more measurements in order to test if this hypothesis holds up.

The investigation of the magnetosphere of Jupiter provides also a unique opportunity to **study the potential extremes of terrestrial space weather**. Statistics of the terrestrial extreme events are very limited and the extremes are not well understood, imposing a great danger to the near-Earth space infrastructure. The investigation of the extreme radiation environment of the

Jovian magnetosphere will drastically advance our knowledge of space weather hazards, protection, and safety. Understanding of the removal of relativistic particles through wave-particle scattering as it occurs in the vicinity of Jupiter's moons (e.g. Nenon+17) may help develop innovative methods of mitigating the terrestrial space weather through the removal of particles. In addition, the in-situ measurements of Jupiter radiation environment is critical for the future exploration of our solar system and expansion of mankind's presence in space.

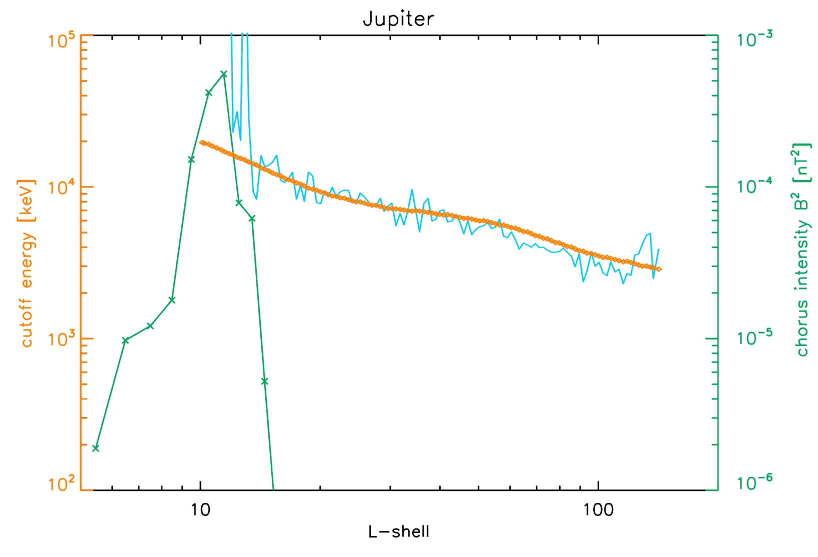


Fig. 2: Jupiter's electron spectra can be approximated through a power law with a sharp cutoff energy beyond which the particle intensities rapidly drop. The blue line shows this cutoff energy, estimated from combining integral measurements. The orange curve compares to adiabatic heating (Kollmann+18), supporting that this is the dominant at large distances and can be studied in isolation. At smaller distances to Jupiter, both chorus wave intensities (green, Menietti+16) and electron intensities rise, suggesting that the dominant physics may switch to local acceleration - just at the point where we run out of reliable measurements.

Additionally, **Jupiter offers the opportunity to discover the importance of processes that are insignificant or obfuscated at Earth** but may play a role in other parts of the universe, as discussed below. Jupiter's high energies cannot be only the result of adiabatic transport and wave-particle interactions, otherwise we would not find particularly MeV electrons at the edge of the magnetosphere (Kollmann+18). Other mechanisms are needed, such as scattering of MeV particles that are accelerated by auroral processes (Mauk+17 Nature) into the equatorial plane or acceleration of protons to tens of MeV via interaction with turbulent electromagnetic fields in plasmoids (Kronberg+19). Also, what was long thought to be a detail, the opposite direction of Jupiter's magnetic field relative to the Earth, appears to be a game changer, enabling large-scale electric fields to be more effective at energizing electrons than at Earth, therefore likely helping Jupiter to be the powerful accelerator we observe (Roussos+18).

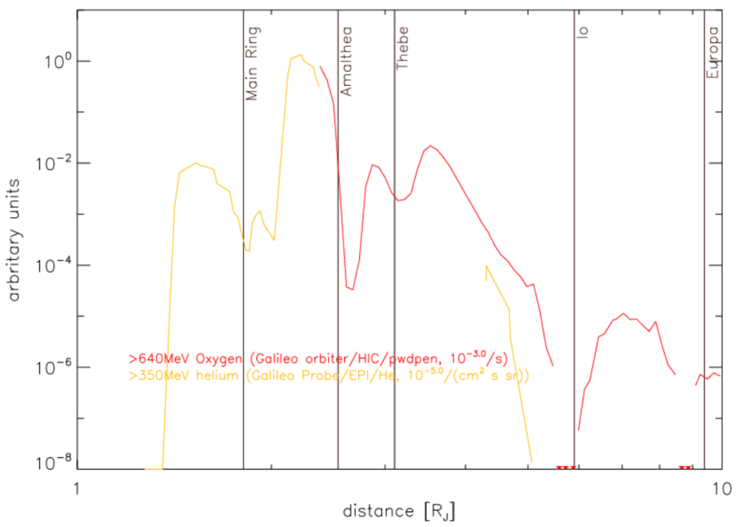
Physics under extremes

Jupiter is the largest natural particle accelerator in our reach. While all sufficiently magnetized planets form radiation belts, Jupiter sets itself apart by having the strongest magnetic field to trap extreme energies, the fastest rotation that drives acceleration, the most powerful auroral processes, and the most geologically active moon that continuously pumps plasma into the magnetosphere that can be accelerated.

Jupiter’s high energy particle intensities are unlike any other planet in our solar system (Mauk+10). While electron intensities at the Earth are significant in excess of several MeV (e.g. Baker+21) or even tens of MeV (Katsavrias+19, Blake+92) only during the most extreme and rare events and spectra usually drop quickly beyond a few MeV (e.g. K.Zhang+20), electron acceleration producing hard spectra to several tens of MeV occurs at Jupiter all the time (e.g. Nenon+17).

The giant size of Jupiter’s magnetosphere allows for acceleration associated with radial transport to occur on enormous spatial scales (100 planetary radii or 10 million km from magnetopause to radiation belts). At the same time, acceleration can occur localized in the relatively small vicinity of Jupiter’s moons. Different to Earth’s moon in the solar wind, the Galileian moons are exposed to sub-Alfvenic plasma flows, creating unique Alfven wing systems and other instabilities that lead to wave production that all set up acceleration paths for electrons and ions (e.g. Shprits+18, Allegrini+19, Clark+22 JGR).

Fig. 3: Jupiter accelerates and traps even relativistic heavy ions at extreme energies. Orange: >90MeV/nuc helium ion fluxes, red: Z≥6 40MeV/nuc count rates (Kollmann+21).



Jupiter offers a wide range of particle species and plasma conditions: Ions as heavy as oxygen and sulfur of different charge states are amongst Jupiter’s major ion species that are accelerated to at least hundreds of MeV, where they have been observed (see Fig. 3). At lower, but still significant quantities, species like Carbon, Sodium, and Magnesium are also present at least up to several 10 MeV/nuc. Such heavy ions in the proton-dominated magnetosphere of Earth are trace species that are largely accelerated externally, either in the form of Anomalous Cosmic Rays or Solar Energetic Particles, whereas at Jupiter the pathway to the relativistic regime for certain ions can start all the way from eV energies and develop fully within the magnetospheric boundaries. The wealth of particle species makes Jupiter ideal to distinguish processes that are mass- and charge-dependent.

Due to its strong magnetic field and internal plasma sources, Jupiter's magnetosphere covers a large range of plasma-beta values (Khurana+04), making its environment conducive to a variety of wave modes and instabilities that can regulate the distribution function of energetic particles. The high plasma beta achieved at medium or large L-shells, contributes to the development of the jovian magnetodisk that on the hand may limit the efficiency of trapping especially high energy ions, but at the same time eases the deep access of solar energetic particles and cosmic rays in the system (Selesnick+01).

Besides being a tool to understand universal processes, Jupiter also harbors its own, specific mysteries. While Jupiter's moons, rings, and gas tori provide an abundant supply of internally produced plasma that can be accelerated, they at the same time also absorb and cool radiation. **Given how strong both particle supply and losses are, it is a mystery why their balance still leads to extreme radiation.** While paradigms such as the dynamics at Jupiter being mostly internally driven have been known for 4 decades (Vaslyunas+83), there are recent indications of solar wind drivers for example playing a role for the auroral current systems (e.g. Nichols+17) and even for the radiation belts that are deeply embedded in the magnetosphere (e.g. Han+18). We therefore can expect that future missions may break even long-standing paradigms.

Astrophysics in our backyard

Plasma is the dominant state of matter in the visible Universe. Already the previous Heliophysics Decadal Survey (National Academies+13) pointed out the importance of studying universal processes because space plasma physics has important implications and "applications to laboratory plasma physics, fusion research, and plasma astrophysics." Jupiter covers such an immense parameter range in plasma, magnetic field, energetic particles, and waves that it has relevance to several astrophysical systems including exoplanets (e.g. Doyle+21). Because of the high energies in its magnetosphere, **Jupiter is the closest analogue to some extrasolar objects** such as pulsars (e.g. Liu+19) and other magnetized stars (e.g. Leto+21), supernova remnants (e.g. Mauk+12), or brown dwarfs (e.g. Williams+18) that we can only observe indirectly through their emissions.

Particularly pulsars and their surrounding supernova remnants share a range of concrete similarities with Jupiter. The magnetic moment of Jupiter is similar to that of a pulsar, meaning that their magnetic fields beyond the radial distance of Jupiter's surface from the respective centers are comparable (Michel+79). Both objects form current sheets and magnetodisks. A pulsar accelerates particles away from its surface in parts through strong electric fields. While the exact mechanism behind these fields is different at Jupiter, electric fields also accelerate particles away from Jupiter in its auroral region (e.g. Mauk+19). The upper end of Jupiter's electron distribution overlaps in energy with the lower end of the distribution in the Crab Nebula, suggesting that Jupiter may allow us to understand the seed population of that famous nebula.

Besides planetary aurora, Jupiter's magnetosphere is the only one in our solar system where energetic particle processes cause it to glow bright in a wide range of wavelengths: For example, energetic electrons can scatter with photons in the inverse Compton effect to create X-rays. The **X-rays can be used to image dynamic electron distributions directly**, without the electrons impacting onto gas, plasma, or surfaces. While at pulsars we can observe these electrons only through their X-rays (R-Y Liu+19), at Jupiter we can observe such X-rays (Numazawa+19, Dunn+22) and the electrons themselves (see Fig. 4).

Jupiter also has the only radiation belts within our reach that produce significant synchrotron emission. Earth does not have the necessary field strengths and Saturn's electrons are blocked by the dense main rings from reaching the strong field regions. Otherwise we mostly know synchrotron emissions from extrasolar sources, such as supernova remnants, or white and brown dwarfs, making it clear that Jupiter can help us to bridge the gap.

Jupiter's MeV electrons and ions also generate X-rays through charge exchange collisions with the planet's atmosphere, rings, and the neutral and plasma tori of Europa and Io. It is thus no surprise that "Jupiter as an exoplanet" or the "In-situ astrophysics of Jupiter" have been the focus of a variety of investigations, since the jovian magnetosphere is the only one that we can study remotely, in the way we observe magnetized objects beyond our solar system, while we can simultaneously obtain ground-truth measurements.

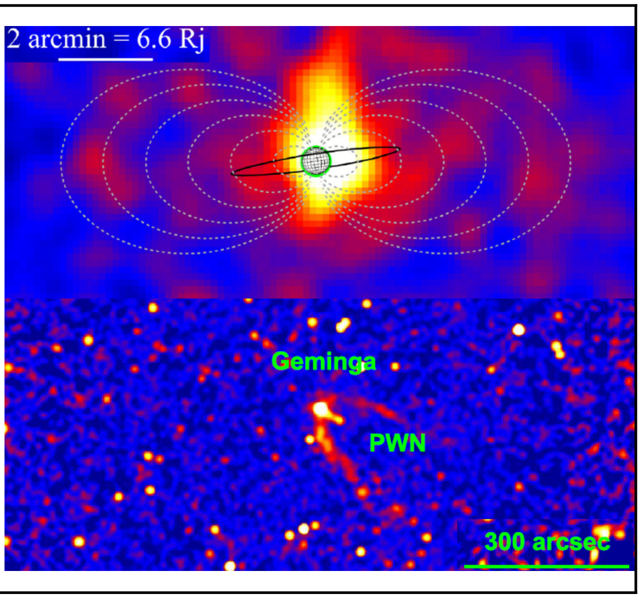


Fig. 4: X-rays produced from electrons scattering with photons. Upper panel: Jupiter at 1-5keV (Numazawa+2019). Lower panel: Geminga pulsar and diffuse pulsar wind nebula at 0.7-2keV (R-Y Liu+2019). The spatial scales of the images are similarly comparable.

Another connection between Jupiter and astrophysics is through its bow shock, which has a relatively high Mach numbers compared to Earth's bow shock. It can therefore be considered as the missing link between supernova shocks and Earth's bow shock. Indeed, bow shocks have been demonstrated to be useful to understand the acceleration of cosmic rays and shocks (including the termination shock) in general (Sulaiman+15; Turner+18 Nature Phys.).

The local production of nearly 1 GeV oxygen ions near some of Jupiter's rings [Roussos+2022], is believed to either come from spallogenic processes that may also occur in icy-polluted white dwarf magnetospheres (Doyle+21), or from acceleration by low frequency waves, as observed in solar and stellar environments (Miller+87).

The need for Heliophysics-centered studies

Current and past missions to Jupiter such as Galileo, Juno, and flyby missions have paved the way for us to ask deeper and more pointed questions regarding the fundamental nature of Jupiter's intense radiation belts (e.g. Bolton+17). However, missions such as SAMPEX and Van Allen Probes, and even short-lived missions such as the CSSWE cubesat, have demonstrated the **value of orbiting spacecraft with dedicated and specifically-designed instrumentation and**

orbits to study radiation belt physics. One major result, obtained after nearly half a century of radiation belt research that was done through missions not focused on radiation, was the unexpected discovery that there are no MeV electrons near the Earth (Fennell+14, X.Li+14, Claudepierre+15, Dudnik+22) and that all previous MeV “electron” observations in the inner belt were actually contamination from very energetic protons.

Today’s situation at Jupiter is like the situation at Earth before SAMPEX. Even the instrumentation and orbits of the upcoming Jupiter missions Europa Clipper and JUICE are optimized to perform only outside of the most intense and energetic radiation, despite the general interest in Jupiter’s radiation. We therefore still cannot even claim that we would reliably know how particles distribute in Jupiter's radiation belts, limiting our ability to understand their origins and physics at work. While a lot of effort is being put into cleaning, correcting, and processing this unique data as best as possible (e.g. Nenon+17, Roussos+21, Kollmann+21), these efforts remain severely limited by the data quality. While radiation models exist (e.g. de Soria-Santacruz+16), they serve mostly mission design and operations and despite best efforts remain as reliable as Earth’s recent "AE9" model (Johnston et al., 2015) that, also despite best efforts, turned out to include more >MeV electrons in the inner belt than truly exist.

The most **critical measurement gap is the lack of energy-resolved measurements at the highest energies**. Most notably, we do not have energy- and direction-resolved information on >1MeV electrons (Kollmann+18) and >20MeV protons (Kollmann+21). While some measurements formally exist, low signal-to-noise ratio within the most intense radiation at L<6 either leads to misidentified particles (e.g. Nenon+18 GRL, Kollmann+22) or the lack of energy resolution obscures the signatures of acceleration processes (e.g. Y-X Hao+20), overall challenging our ability to make sound interpretations. We only have a few, often indirect measurements of ion charge states (e.g. Clark+16) that hold clues of the ionization location and acceleration steps of ions (Smith+19). The 3D wave vector that is critical in determining the efficiency of wave-particle interaction (Shprits+09) remains unmeasured (e.g. Kurth+17). By design, **previous Jupiter missions spent little time in the radiation belts** to reduce dose. We show in a companion White Paper (Clark+22) that a mission that dives into the heart of Jupiter’s radiation belts and makes clean measurements is feasible and necessary to unlock their secrets.

Traditionally, planetary magnetospheres have been studied through NASA’s Planetary Sciences division. After the initial survey of Jupiter and Saturn by flagship missions with a broad scientific focus, future missions will mostly be focused on specific questions that will derive from the Decadal Strategy for Planetary Science and Astrobiology 2023-2032 that covers the broad areas of solar system origins, structure and dynamics of various worlds, and life and does not highlight space plasma physics (National Academies+22). Either way, **space plasma physics at planetary systems is most relevant to the defined focus of NASA’s Heliophysics division**.

An additional tool to increase the focus on space physics throughout the heliosphere in the future may be the support of cross-divisional opportunities where a future Planetary mission receives augmentation from the Heliophysics division (Cohen+22). In any case, the trend of Heliophysics studying other planets is well justified and should continue. Jupiter in particular is an ideal laboratory to study a wide range of space physics processes, particularly extreme particle acceleration, and should therefore be a priority target for future Heliophysics missions.

References

Allegrini+19, JGR, https://doi.org/10.1029/2019JA027693
Baker+21, SSR, https://doi.org/10.1007/s11214-021-00838-3
Blake+92, GRL, https://doi.org/10.1029/92GL00624
Bolton+17, SSR, https://doi.org/10.1007/s11214-017-0429-6
Claudepierre+15, JGR, https://doi.org/10.1002/2015JA021171
Clark+16, JGR, https://doi.org/10.1002/2015JA022257
Clark+22, JGR, https://doi.org/10.1029/2020GL090839
Clark+22, accompanying White Paper, COMPASS Mission to Jupiter's Extreme Magnetosphere
Cohen+22, accompanying White Paper, Studying planetary magnetospheres in Heliophysics
Crary+22, accompanying White Paper, Magnetosphere of Jupiter
Dunn+22, accompanying White Paper, Orbiting X-ray Instrument in the Jovian System
de Soria-Santacruz+16, JGR, https://doi.org/10.1002/2016JA023059
Dudnik+22, ASR, https://doi.org/10.1016/j.asr.2022.06.031
Doyle+21, ApJL, https://doi.org/10.3847/2041-8213/abd9ba
Fennel+14, GRL, https://doi.org/10.1002/2014GL062874
Y-X Hao, Y-Su Sun, E. Roussos+20, ApJL, https://doi.org/10.3847/2041-8213/abca3f
Han+18, JGR, https://doi.org/10.1029/2018JA025849
Katsavrias+19, JGR, https://doi.org/10.1029/2019JA026743
Kollmann+18, JGR, https://doi.org/10.1029/2018JA025665
Kollmann+21, JGR, https://doi.org/10.1029/2020JA028925
Kollmann+22, accompanying White Paper, The Need for High SNR Measurements
Horne+98, GRL, https://doi.org/10.1029/98GL01002
Kronberg+19, JGR, https://doi.org/10.1029/2019JA026553
Kruth+17, SSR, https://doi.org/10.1007/s11214-017-0396-y
Khurana+04, Cambridge Uni. Press, The Configuration of Jupiter's Magnetosphere
Leto+21, MNRAS, https://doi.org/10.1093/mnras/stab2168
X. Li+14, JGR, https://doi.org/10.1002/2014JA020777
R.-Y. Liu+19, ApJ, https://doi.org/10.3847/1538-4357/ab125c
Mauk+10, JGR, https://doi.org/10.1029/2010JA015660
Mauk+12, Geophys. M. S., https://doi.org/10.1029/2012GM001305
Mauk+17, Nature, https://doi.org/10.1038/nature23648
Mauk+19, JGR, https://doi.org/10.1029/2019JA027699
Mann+16, Nat. Phys., https://doi.org/10.1038/NPHYS3799
Menietti+16, JGR, https://doi.org/10.1002/2016JA022969
Michel+79, SSR, https://doi.org/10.1007/BF00172210
Miller+87, Sol.Phys., https://doi.org/10.1007/BF00147698
National Academies+13, Nat. A. Press, https://doi.org/10.17226/13060
National Academies+22, Nat. A. Press, https://doi.org/10.17226/26522
Nenon+17, JGR, https://doi.org/10.1002/2017JA023893
Nenon+18, JGR, https://doi.org/10.1029/2018JA025216
Nenon+18, GRL, https://doi.org/10.1029/2018GL080157
Nichols+17, GRL, https://doi.org/10.1002/2017GL073029
Numazawa+19, P. Astrn. S. Jpn., https://doi.org/10.1093/pasj/psz077

Roussos+18, Icarus, https://doi.org/10.1016/j.icarus.2018.01.016
Roussos+22, Science Adv., https://doi.org/10.1126/sciadv.abm4234
Reeves+15, JGR, https://doi.org/10.1002/2015JA021569
Selesnick+01, https://doi.org/10.1029/2000JA000242
Schulz+74, Springer, https://doi.org/10.1007/978-3-642-65675-0
Sulaiman+15, PRL, https://doi.org/10.1103/PhysRevLett.115.125001
Shprits+09, JGR, https://doi.org/10.1029/2009JA014223
Shprits+13, Nat. Phys., https://doi.org/10.1038/NPHYS2760
Shprits+18, Nature Com., https://doi.org/10.1038/s41467-018-05431-x
Smith+19, ApJ, https://doi.org/10.3847/1538-4357/aaed38
Turner, Nature Phys., https://doi.org/10.1038/s41586-018-0472-9
Vasyliunas+83, Cambridge book, https://doi.org/10.1017/CBO9780511564574.013
Williams+18, Handbk. of Exoplanets, https://doi.org/10.1007/978-3-319-30648-3_171-1
Woodfield+14, JGR, https://doi.org/10.1002/2014JA019891
K. Zhang+20, JGR, https://doi.org/10.1029/2020JA028511