Airo International Journal
Peer-Reviewed
Multidisciplinary

ISSN: 2320-3714
Volume:1 Issue:2
February 2025
Impact Factor:10.2
Subject: Physics

EXPLORING ADVANCEMENTS IN SPACE PHYSICS THROUGH RESEARCH IN RADIO AND SPACE PHYSICS

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Abstract

This study investigates the mechanisms by which Kelvin-Helmholtz Instabilities (KHIs) manifest in various interplanetary magnetic field (IMF) scenarios along the magnetopause boundaries of Neptune and Uranus. The magneto sheath separates the shocked solar wind plasma from the magnetospheric plasma, and an analytical model is used to study its dynamics. The model determines the likelihood of KHI generation under different orientations and IMF strengths (ranging from 0.01 to 1.0 nT), taking into consideration constant densities for the solar wind and magnetosphere. The results demonstrate that the magnetopauses of the two planets are conducive to the formation of KHI, particularly at low values of the IMF. Further from the subsolar point, where there is no diurnal or seasonal variation, KHI production is more likely to take place. The Neptunian magnetopause shows a stronger tendency to produce KHI at higher IMF intensity. These results highlight the importance of considering KHI dynamics in future space missions to the outer solar system for understanding plasma transport and magnetospheric processes at Neptune and Uranus. The study also suggests that future studies use high-resolution models to account for variations in solar wind interaction that are time-dependent.

Keywords: *Kelvin-Helmholtz Instabilities, Magnetopause, Uranus, Neptune, Interplanetary Magnetic Field (IMF).*

1. INTRODUCTION

The multidisciplinary discipline of space physics is devoted to comprehending the physical mechanisms governing the motion of magnetic fields, matter, and energy in space (Arm, 2023). Significant progress has been made in this field of study in recent decades, particularly as radio and space physics have become more and more influential. These fields have become instrumental in examining the interactions between solar winds, planetary magnetospheres, cosmic radiation, and other phenomena that shape the space environment (Mohammadi, 2009). Understanding the basic dynamics governing space weather, celestial body electromagnetic behaviour, and the processes operating in the vast expanse of space has become more and more crucial as space exploration advances. This is true not only for scholarly purposes but also for real-world uses in satellite communication, space missions, and terrestrial technologies (Prestage, 2007).

We now have a better knowledge of how charged particles and magnetic fields behave in space because to research in radio and space physics. In order to better understand the intricate systems that govern space weather phenomena like solar flares, geomagnetic storms, and the aurora borealis, scientists are able to investigate the properties of planetary atmospheres, ionospheres, and magnetospheres by examining how radio waves travel through space (Gary, 2022). These phenomena, which originate from the Sun, can have profound effects on Earth-based technologies, including satellite systems, GPS navigation, communication networks, and even power grids. As a result, radio and space physics research has become crucial not only for advancing scientific knowledge but also for ensuring the safety and security of infrastructure that depends on space-based technologies (Kasper J. L.-W., 2021).

Space physics study is important not only on Earth but also in the universe at large (Bi, 2022). The origin and evolution of planetary systems can be better understood by studying the physical processes operating in the magnetospheres of other planets. Jupiter, Saturn, Uranus, and Neptune are gas giants and ice giants, respectively. By studying their magnetospheres, we can learn more about charged particle dynamics, how planetary magnetic fields behave, and how solar winds shape planetary environments. Just as studying cosmic rays and interstellar magnetic fields can shed light on the cosmos and its structure, so can studying the interplay between these two cosmic forces (Zarka, 2004).

Technological advancements in observational methods, such as the development of radio telescopes, space probes, and satellites, have dramatically enhanced the ability to study these space phenomena. These tools allow scientists to gather real-time data on the conditions of space weather and its interactions with planetary bodies, paving the way for more detailed and accurate models of space systems. Additionally, computational techniques such as numerical simulations and data analysis tools enable researchers to create sophisticated models of space plasma dynamics, magnetic field interactions, and other complex space phenomena (Chi, 2022).

2. LITERATURE REVIEW

Bentum et al. (2020) found that low-frequency radio astronomy, especially above 30 MHz, has regained attention thanks to programs like LOFAR and ILT. However, observations below 30 MHz were limited by solar eruptions, radio wave reflection below 10 MHz, ionospheric distortions, and RFI. To tackle these challenges, Dutch scientists developed the OLFAR project, a space-based ultra-low-frequency radio telescope that views the Universe's dark ages, analyzes solar bursts, and studies planetary systems using a swarm of satellites. The first stage of the NCLE experiment was launched in May 2018 as part of China's Chang'e 4 mission. The objective was to provide valuable data to aid in the creation of future technology for such a massive project (Bentum, 2020).

Panda et al. (2023) examined that Our knowledge of the universe has greatly increased because to radio astronomy, which uses radio waves to examine celestial objects. Astronomers have made important discoveries concerning dark matter, dark energy, and the birth of the universe because to this field, which has allowed them to view objects like pulsars, quasars, and cosmic microwave background radiation. By detecting signals from far-off cosmic sources, radio telescopes have helped scientists learn more about the evolution of stars, galaxies, and other celestial bodies. All things considered, radio astronomy has emerged as a crucial instrument in astrophysics and cosmology, providing deep understanding of the universe's secrets (Panda, 2023).

Carley et al. (2020) phased array interferometer distributed across Europe and the Netherlands that operates in the 10-240 MHz frequency range for a number of astrophysical research purposes. Despite its initial lack of concentration on heliophysics or space weather, the "LOFAR for Space Weather" (LOFAR4SW) project aimed to enhance space weather science and operations by updating the system to investigate Jupiter, the Sun, Earth's ionosphere, and heliosphere. This study aimed to enhance space weather operations and research by analyzing the existing space weather radio network and contrasting possible improvements (Carley, 2020).

Lan et al. (2021) offered a comprehensive evaluation of astrophysics visualization, reviewing key publications in the fields of both visualization and astrophysics. The current visualization techniques were categorized into five parts: data wrangling, data exploration, feature identification, object reconstruction, and education/outreach. The work offered a unique contribution by highlighting the challenges and opportunities of applying visualization techniques in astrophysics, combining the opinions of astronomers and visualization specialists. The primary goal was to provide a framework for integrating state-of-the-art data visualization and analysis methods with the massive astronomical datasets (Lan, 2021).

3. RESEARCH METHODOLOGY

The goal of this investigation is to learn more about the magnetopause boundary, which separates the magnetosheath plasma from the magnetospheric plasma, assuming that the plasmas involved are incompressible. We considered constant magnetosphere and solar wind densities for all planets under various upstream interplanetary magnetic field (IMF) conditions, spanning from 0.01, 0.1, 0.3, 0.5, and 1.0 nT, and encompassing several IMF orientations. This study investigated the conditions necessary for the creation of Kelvin-Helmholtz instability (KHI) in planetary magnetospheres and tested the hypothesis that KHI might emerge at the magnetopause boundary in such a system (Freeman, 2020).

$$[\mathbf{k} \cdot (\mathbf{v_1} - \mathbf{v_2})]^2 > \frac{1}{\mu_0}\left(\frac{1}{\rho_1} + \frac{1}{\rho_2}\right)\left[(\mathbf{k} \cdot \mathbf{B_1})^2 + (\mathbf{k} \cdot \mathbf{B_2})^2\right] \tag{1}$$

The border of the magnetopause is defined by the interaction of the shocked solar wind plasma in the magnetosheath with the magnetospheric plasma, with respect to factors such as the wave vector (k) along the magnetopause, the shocked solar wind velocity (v1), and the magnetospheric plasma velocity (v2). In addition, they comprise the following: the solar wind density (ρ1), the magnetospheric density (ρ2), the planetary magnetic field (B2) at the magnetopause boundary, and the interplanetary magnetic field (IMF) that the solar wind carries (B1) following its modification in the magnetosheath by the plasma depletion layer (Ma, 2022).

Kelvin-Helmholtz instability (KHI) formation dynamics are controlled by the velocity shear between the two plasmas, which is more likely to cause instability when it coincides with the wave vector (Bisi, 2015). When stabilizing forces like the planetary magnetic field or the strength of the IMF are strong and aligned with the wave vector, they tend to suppress the creation of KHI. This results in a larger magnetic tension and a lower probability of instability. The intricate interactions among solar wind conditions, planetary magnetospheres, and the possibility of kinetic instabilities at the magnetopause are highlighted by this model (Rauf, 2023).

In this work, the Kelvin-Helmholtz instability (KHI) propagation direction along the magnetopause is defined by the wave vector (k). Phase and group velocities of the KHI are parallel to the magnetopause interface for incompressible plasmas instead. We utilize a first-order approximation to make the analysis simpler, allowing us to ascertain the direction of the magnetopause's constituents by considering the wave vector to be tangential to the surface. This method facilitates comprehension of the spatial dynamics of KHI creation at the solar wind-magnetosphere interface, as impacted by changing solar wind and planetary magnetic field circumstances (Vourlidas, 2020).

The wave vector k indicates the direction of propagation of the KHI. The group and phase velocities of KH waves in incompressible plasmas are always perpendicular to the interface. A first-order approximation of the wave vector as perpendicular to the magnetopause surface is used to ascertain the vector components' directional orientation (Wang, 2022).

The wavenumber is defined as $k = \frac{2\pi}{\lambda}$ where the wavelength of the instability λ is limited by the length scales of the magnetosphere system. The gyroradius of the plasma in the PDL is determined to be about 0.01 of a planetary radius (R) when the incoming solar wind is |B| = 0.01 nT for both planets. The fastest growing KH wavelength has a spatial period lower bound of $2\pi\Delta$, where Δ is the scale length of the shear layer. Therefore, a physically reasonable lower bound for the wavelength would be $\lambda = 2\pi 0.01$ R. This gives a corresponding wave vector upper bound of $k = 100\mathrm{R}^{-1}$. The thickness of the magnetosheath (5.7 R_U and 8.4 R_N) sets the upper bound on the KHI wavelength for each model, and the wave vector lower bound of $1.1R_U^{-1}$ and $0.75R_N^{-1}$ (Thornton, 2013).

Therefore, the k value is confined between:

$$\begin{aligned} 1.1\,R_U^{-1} &< k < 100\,R_U^{-1} \\ 0.75\,R_N^{-1} &< k < 100\,R_N^{-1} \end{aligned} \tag{2}$$

This study's results are for k = 2R−1, and for the purposes of this paper, any k value in the range will not affect where KHIs are prohibited because, as in Equation 1, both sides will scale with k2. Nevertheless, we point out that this analysis is still significant because it shows that KHIs can form when the k value is within this physically valid range (Asmar, 2022).

To determine the likelihood that the KHI will occur at any location along the magnetopause, magnetosphere and magnetosheath data are obtained from either side of the paraboloid surface and utilized in Equation 1. As each ice giant's slanted magnetic dipoles precess around the rotating axis, the vector orientation in Equation 1 changes (Barbosa, 2021).

4. RESULTS & DISCUSSION

Given the condition for KHIs to develop (Equation 1) we characterized the solar wind-magnetosphere interaction at Uranus and Neptune by determining which points along the magnetopause can become KH unstable. The likelihood of KHIs evolving is the result of several physical factors, including the IMF strength, IMF direction, season, and the rotation phase of the magnetosphere. We evaluate the solar wind-magnetosphere interaction by varying each of these components and display the results as a 2D projection of the magnetopause showing the regions where KHIs can evolve (Berngardt, 2017).

The results are shown for the IMF component in the z direction. At both Uranus and Neptune, Voyager 2 measured the magnetic field just outside their magnetospheres, as being primarily in the Bz direction, at Bz ≈ 0.1 nT. The Parker spiral suggests that the IMF should also be present in the By direction. Hence, we chose to apply the model for each of the following orientations: B = Bz, B = By, and B = Bzy. Figures 1 and 2 only show results at 0.01 and 0.5 nT. This is because these values represent a range that covers both theoretical predictions and observed values of IMF strength (Kanatas, 2017).

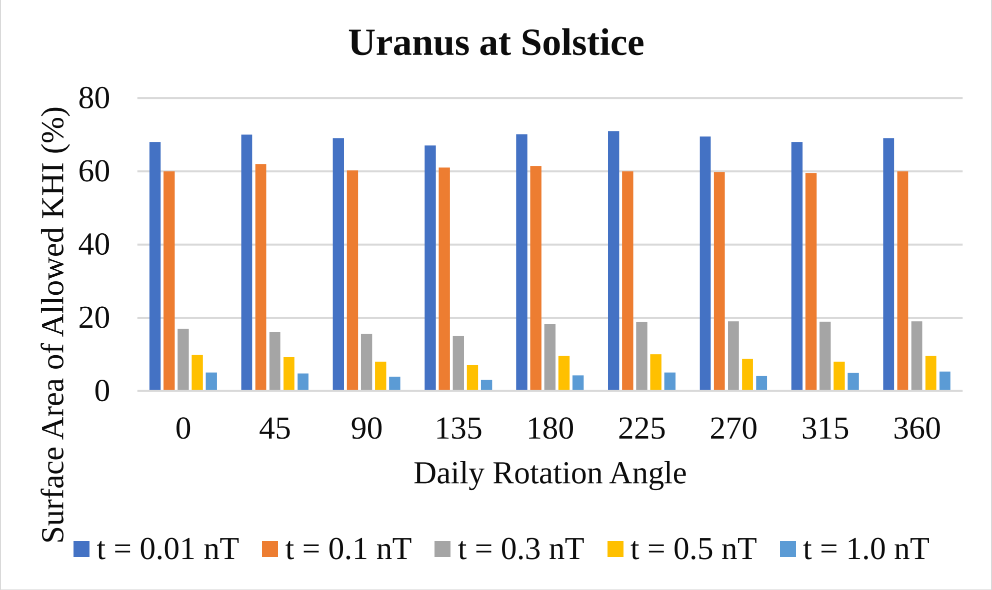

Fig. 1(a)

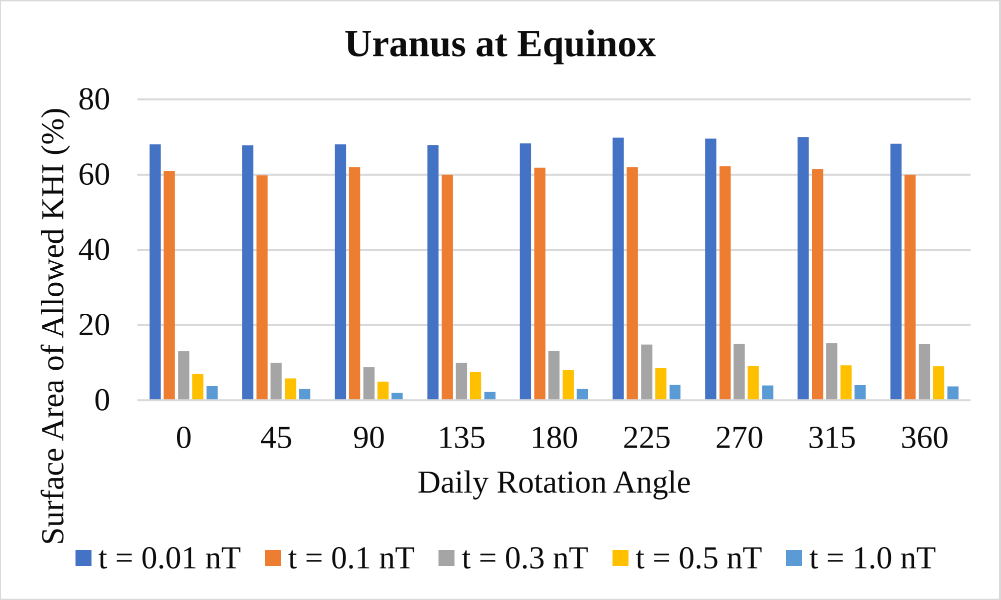

Fig 1(b)

Figure 1 (a, b): The potential KHI surface area at Uranus at the solstice (left) and equinox (right) under different IMF variables. Colour dictates IMF magnitude; red indicates |B|=0.01 nT, blue indicates |B|=0.1 nT, black indicates |B|=0.3 nT, yellow indicates |B|=0.5 nT, and green indicates |B|= 1.0 nT. The intensity-modulated field (IMF) is shown by solid lines when it is entirely Bz, dotted lines when it is entirely By, and dashed lines when it is evenly divided between Bz and By to derive the magnitude of |B| (Frissell, 2023).

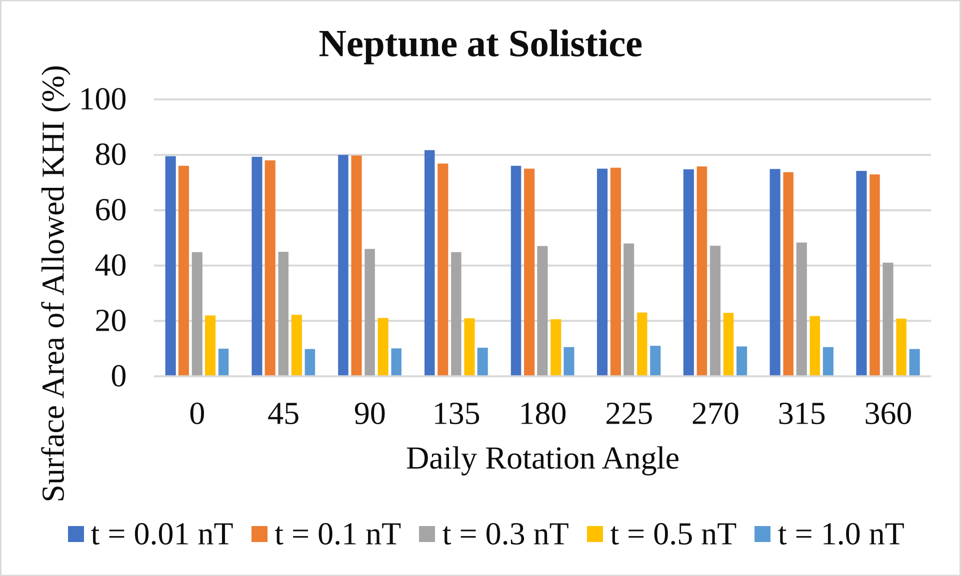

Fig. 2(a)

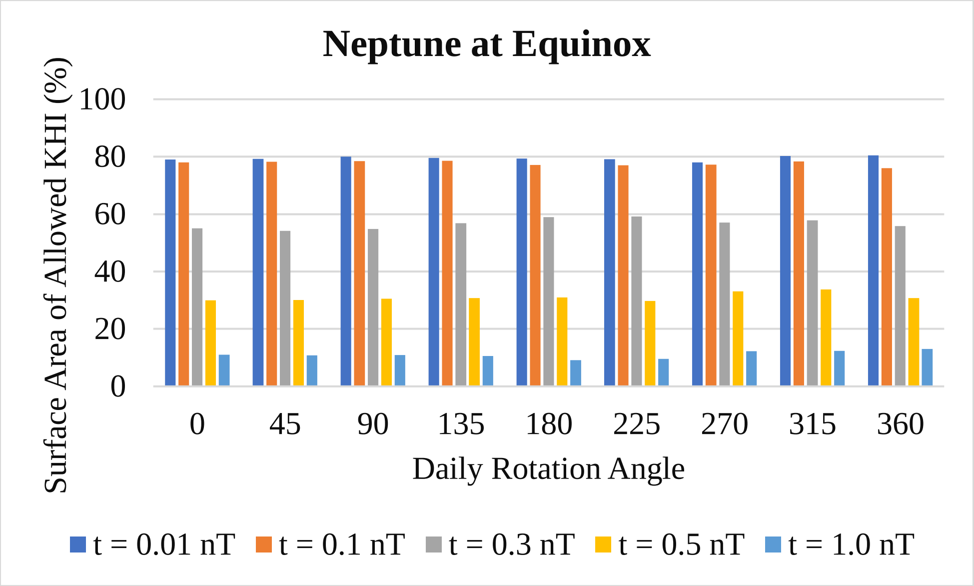

Fig. 2(b)

Figure 2 (a, b): The potential KHI surface area at Neptune during solstices (left) and equinoxes (right) under different IMF scenarios. Colour dictates IMF magnitude; red indicates |B|=0.01 nT, blue indicates |B|=0.1 nT, black indicates |B|=0.3 nT, yellow indicates |B|=0.5 nT, and green indicates |B|= 1.0 nT. Dashed lines show the IMF divided evenly between Bz and By to get the

|B|, dotted lines show the IMF primarily by By, and solid lines show the IMF solely by Bz (Streltsov, 2018).

The results of this analytical model suggest that the KHI may be crucial in regulating the flow of plasma into the magnetosphere in the ice-giants. As a function of rotation phase, season, and the IMF, the model results also shed important light on potential processes at the magnetopauses of the ice giants (Prölss, 2012). In addition to providing context for these model predictions, the Uranus Orbiter and Probe's (UOP) in-situ measurements will be crucial to comprehending the dynamic evolution of the system. Determining the threshold at which KHIs grow at Uranus will specifically depend on obtaining observations of the circumstances across the magnetopause boundary that quantitatively constrain the plasma density, flow, and magnetic field. In a similar vein, observations along the magnetopause barrier could be made by a future Neptune system mission, like the Neptune Odyssey concept study, in order to compare the dynamics of the two ice giants (Kallenrode, 2013).

KHIs' impact on particle transport and plasma heating through shocked solar wind transportation into the planets' magnetospheres serves as further motivation for in-situ research of KHIs in the outer solar system. At Uranus, Voyager 2 detected a "vacuum" magnetosphere (Burke, 2019). Solar wind transport into Uranus' magnetosphere may be crucial to the planet's magnetospheric dynamics, affecting magnetic storms and the aurora due to the absence of internal plasma sources. The reconnection voltage can be used to examine the importance of magnetic flux transmission by reconnection through the Dungey cycle (Asmar S. W., 2019). However, whether a faster rate of magnetic flux transport into Uranus' magnetosphere is due to viscous interactions or Dungey cycle reconnection is unknown. Moreover, KHIs are linked to the production of ultralow frequency (ULF) waves on Earth, which have the ability to accelerate and move electrons in the radiation belt. The electron radiation belt was more intense than the proton radiation belt, according to Voyager 2's measurements of Uranus' radiation belts. Although our knowledge of radiation belt dynamics at Uranus is still developing, the asymmetry in Uranus' magnetic field may be the cause of the weak proton radiation belt. Therefore, to learn more about the magnetospheres of the ice giants, in situ observations of these interactions are essential (Pannuti, 2020).

For all investigated parameters, the KH viscous interaction is permitted to develop over most of the magnetosphere boundary for both Uranus and Neptune (with the exception of the area surrounding the subsolar point). In Masters, a complementary analysis was conducted on the probability of reconnection at Uranus and Neptune, respectively. According to Masters' research, reconnection is forbidden over most of the magnetopause, with the subsolar point of the magnetopause being the main location where it is permitted. The KH viscous interaction may be the predominant mode of energy transmission at Neptune and Uranus, according to their study and the findings in this paper (Sjöholm, 2009).

For the locations where KHIs are permitted, Figures 1 and 2 show little seasonal and diurnal variation, indicating that IMF strength is the main factor determining the nature of the solar wind-magnetosphere interaction, even for planets in turbulent systems. This work represents snapshots of the system in time because it was carried out using a static analytical model. We tested a variety of initial inputs to account for the time fluctuation of the solar wind velocity and discovered that KHI production varied very little. In order to assess how the nature of the interaction and the growth of KHIs change over time, future research should examine the solar wind interaction using high-resolution multifluid magnetohydrodynamic models (Paramasivam, 2013).

We also point out that while space plasmas are better described by compressible fluids, we assumed that plasmas were incompressible fluids when we formulated our analytical model. By stabilizing the KHI, plasma compressibility lowers the likelihood that a KHI will form. Additionally, the impact of currents on the magnetopause boundary, which were left out for convenience, may be included in future research (Kasper, 2020).

5. CONCLUSION

In conclusion, this study assessed the possibility of Kelvin-Helmholtz Instabilities (KHIs) occurring at the magnetopause boundaries of Uranus and Neptune using an analytical model. The findings suggest that the magnetopause limits of both planets are suitable sites for the creation of KHI (Hamidi, 2014). In particular, KHIs are allowed on vast, consistent magnetopause surface regions over the course of a planetary day at low Interplanetary Magnetic Field (IMF) values. Additionally, the fraction of surface area that is favourable for KHI creation is constant throughout the year and IMF values. Although KHIs are always forbidden at the magnetopause's nose, they can form on the flanks, especially when the IMF is high. Neptune seems more conducive to KHI creation at higher IMF values, even if the results for Uranus and Neptune are comparable (Molera Calvés, 2012). These findings highlight the necessity of taking into consideration viscous plasma transport when assessing the density and composition of the magnetospheres, as well as the possibility of KHIs while planning tour itineraries and magnetopause crossing sites for future missions to the outer solar system.

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