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MISSION DESIGN FOR THE EXPLORATION OF ICE GIANTS, KUIPER BELT OBJECTS AND THEIR MOONS USING KILOPOWER ELECTRIC PROPULSION

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The exploration of Ice Giants, Kuiper Belt Objects (KBOs) and their moons poses unique challenges from a mission design standpoint. NASA is currently developing a scalable 1-10 kW-electric space fission reactor, known as Kilopower, that may be useful in solving these challenges. The focus of this paper is to investigate the applicability of Kilopower Electric Propulsion to orbiting missions to Uranus, Neptune, and Pluto. This effort is broken into two parts for each destination. First, a broad search of interplanetary trajectories with multiple gravity assists is completed to identify a range of mission opportunities from 2025 to 2045. Second, preliminary analysis is completed to understand the accessibility of various destination orbits, including elliptical orbits around the primary body and circular orbits around the largest moons. Results suggest that orbital missions to Uranus and Neptune are feasible with reasonable time of flight on medium class launch vehicles. Further work is necessary to achieve similar success with Pluto missions, but preliminary results are promising.

INTRODUCTION

Ice Giants, Kuiper Belt Objects (KBOs) and their moons represent some of the final frontiers of solar system exploration. Their immense distances from both the Earth and the Sun pose unique challenges from a mission design standpoint. Concepts for missions that can orbit these bodies in the far reaches of the outer solar system, in a reasonable amount of time, often require small spacecraft, powerful launch vehicles, enormous chemical insertion burns or aerocapture. Further complicating the mission, limited solar irradiance at such distances makes solar power impractical.

Radioisotope Electric Propulsion (REP)[1–4] has been proposed and studied for outer planet exploration as a means of overcoming some of the aforementioned challenges. REP systems generally fall in the 1 kW class power range and provide limited propulsive capability unless the spacecraft is small. Further, reliance upon a limited supply of Plutonium-238 makes securing a sizable amount of the needed fuel challenging. Nuclear Electric Propulsion (NEP)[5–10] has also been proposed and studied for outer planet exploration. Typical NEP studies assume a system power of 100 kW or

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more and may require multiple launches with in-space assembly. Such massive, high power systems can lead to the design of a spacecraft that is costly and may require considerable technology development.

NASA is currently developing a scalable 1-10 kW-electric (kW_e) space fission reactor, known as Kilopower.[11,12] The Kilopower Reactor Using Stirling Technology (KRUSTY) experiment, which included a 28-hour, full-power test that simulated a mission, including reactor startup, ramp to full power, steady operation and shutdown, was successfully completed in March 2018.* The KRUSTY test was performed on a 1 kW_e-class system, but the reactor design approach and operational characteristics are applicable for systems up to *at least* 10 kW_e. Combined with existing electric hall thrusters or ion engines, a Kilopower Electric Propulsion (KEP) system could uniquely enable Ice Giant and KBO exploration while avoiding some of the common pitfalls of REP or NEP systems. KEP could provide more propulsive capability than REP while using a more readily available Uranium fuel source. Unlike very high power NEP systems, KEP could be integrated into a smaller spacecraft with less need for costly technology development programs.

The focus of this paper is to investigate the applicability of KEP, from a mission design perspective, for orbiting missions to Uranus, Neptune, and Pluto. This effort is broken into two parts for each destination. First, a broad search of interplanetary trajectories with multiple gravity assists is completed to identify a range of mission opportunities from 2025 to 2045. Previous studies have completed a similar broad search of interplanetary trajectories to Ice Giants using chemical propulsion, REP and Solar Electric Propulsion (SEP).[13–15] For each destination, multiple launch vehicles and time of flight (TOF) limits are explored to better understand the trade space.

Second, preliminary analysis is completed to understand the accessibility of various orbits around the primary body. Preliminary low thrust orbit insertion analysis to elliptical orbits of varying periods is completed for a range of spacecraft masses. In addition, preliminary analysis of low thrust transfers to circular orbits around major satellites (Titania, Triton, and Charon) is completed to estimate the TOF and propellant required to reach different circular orbit altitudes.

METHODOLOGY

This section outlines the methods and assumptions used throughout this study. This includes ground rules and assumptions for a representative spacecraft, as well as the methods used for the broad search of interplanetary trajectories, and the low thrust orbit insertion analysis.

Spacecraft Assumptions

Low thrust trajectories using electric propulsion are tightly coupled with the spacecraft that is intended to fly them. Of primary significance are the electrical power level available to the propulsion system, the thruster configuration, and the spacecraft mass. For the purposes of this study, a representative spacecraft design has been assumed based on a past Compass[16] design of a KBO orbiter using a similar KEP system as shown in Figure 1. From the master equipment list of this design, the dry mass of a similar spacecraft with a 10 kW_e Kilopower system, 2+1 NEXT-C[17] ion engines and 100 kg reserved for science payload is estimated (with appropriate system margin) to be 2,560 kg + 6% of the required propellant mass for tankage. This value serves as a basis of comparison to determine what trajectories are feasible for this class of spacecraft, but it is not used in designing

*https://www.nasa.gov/press-release/demonstration-proves-nuclear-fission-system-can-provide-space-exploration-power the trajectories. Therefore, the same set of solutions can be used if this dry mass value changes. The only difference will be which solutions are deemed feasible.

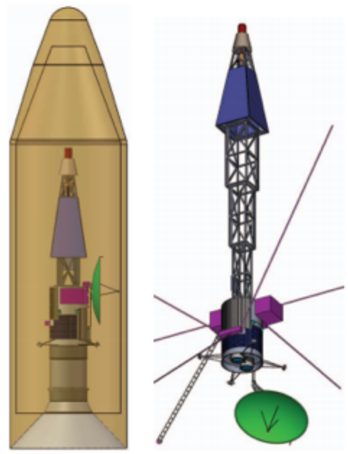

Figure 1. Compass design for a KBO orbiter using KEP.

Interplanetary Trajectory

The broad search of interplanetary trajectories begins with a grid search method using a lambert solver to build a set of candidate initial guesses while considering every reasonable 2, 3 or 4 flyby (FB) sequence, similar to that used by Landau[13] and Lam.[18] Figure 2 provides a schematic overview of this process. For a given launch date and FB sequence, a series of nested for-loops solve Lambert's problem for an incremental range of TOFs from each body to the next. Trajectories are filtered as early as possible along the way based on a number of criteria. First, the departure characteristic energy (C_3) must be less than a specified limit (Max C_3). Then, at each FB, two conditions are assessed. The total TOF (ΔT_{total}) plus the TOF to the next body ($\Delta T+$) must be less than a maximum TOF (ΔT_{max}). Also, if the difference between the inbound velocity (V_{in}) and the outbound velocity to the next body (V_{out}) is greater than the maximum ΔV that the body can provide (ΔV_{FB}), the difference must be less than a specified limit (ΔV_{max}). It is assumed that this difference can be resolved by the propulsion system and optimization of encounter dates. Finally, the final arrival V_{in} must be less a maximum value. Trajectories that pass through all filters are stored as feasible initial guesses. This process is easily parallelized by discretizing into independent subproblems that solve for all FB sequences with a single launch date. Table 1 shows various parameters used for the initial guess step.

The goal of this process is to provide a good enough initial guess to point the optimizer in the right direction. It is assumed that initial guesses that are similar enough will optimize to the same (or similar) solutions, so a second step is added to further reduce the number of initial guess by eliminating near-duplicates. This step compares departure C_3 and body encounter dates of nearby guesses and eliminates those that are the same to within a tolerance. This step can dramatically reduce the number of initial guesses to be optimized by upwards of 90%. Table 2 shows the number of trajectories at each step of the process. An example of an initial guess for an Uranus trajectory is shown in Figure 3. The optimized version is shown later in Figure 9.

The final set of initial guesses that pass through all filters are then optimized as low thrust tra-

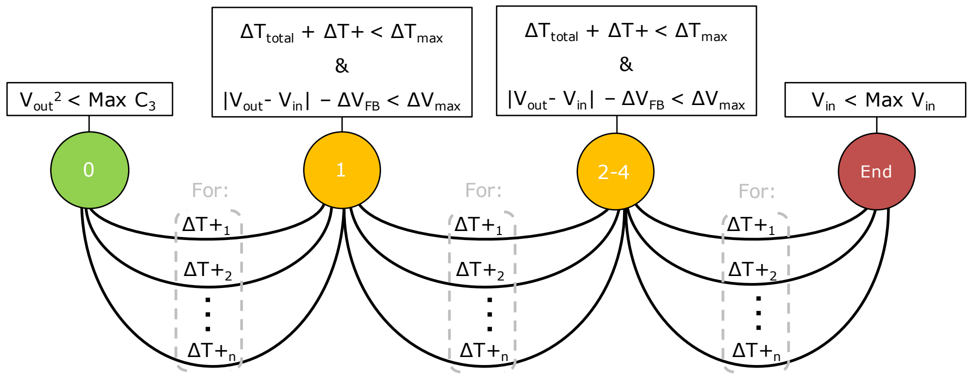

Figure 2. Schematic of the algorithm used to generate candidate initial guesses for further optimization.

Table 1. A summary of various parameters used for the initial guess step

Metric	Value	Note
Launch Dates	1/1/2025 - 1/1/2045	15-day step size
Max C_3	200 km^2/s^2 / # of FBs	-
ΔT+ (inner-inner)	15 - 1095 days	15-day step size
ΔT+ (otherwise)	100 - 4750 days	30-day step size
ΔT_{max}	13, 15, or 16 years	For Uranus, Neptune, or Pluto
ΔV_{max}	3 km/s	3.5 km/s on longer final leg
Final V_{in}	13, 16, or 17 km/s	For Uranus, Neptune, or Pluto
FB Bodies	E,V,M,J,S,U,N	All planets except Mercury

Table 2. Number of initial guess for 2, 3, and 4 FB trajectories to Uranus, Neptune and Pluto.

Planet	Possible	Feasible	Optimized
Uranus	$> 10^{13}$	$\approx$ 500,000	6,321
Neptune	$> 10^{13}$	$\approx$ 350,000	4,163
Pluto	$> 10^{13}$	$\approx$ 45,000	542

jectories using EMTG[19,20] to maximize the dry mass. Table 3 provides an overview of various parameters used for optimization. The power margin, duty cycle and propellant margin are 10%, 90%, and 15%, respectively. It is assumed that 6% of the propellant margin corresponds to that required for tankage. By carrying the tankage this way, the maximized dry mass can be compared directly to the 2,560 kg estimated non-tankage dry mass from the spacecraft assumptions. It is important to note, however, that what is referred to as the ”dry mass” for the interplanetary trajectories must also include any propellant required for propulsive maneuvers after arrival at the destination. All interplanetary trajectories arrive at the destination with a V_∞ of 0 km/s. All initial guesses are separately optimized for launches on an Atlas V 551 (AV), Delta IV Heavy (DIVH), and Space Launch System Block 1 (SLSB1). Since Kilopower is assumed to provide constant power throughout the mission, the two NEXT-C thrusters operate at a constant I_{sp} and thrust of 3,968 s and 0.280 N, respectively. This corresponds to each operating at 4.5 kW (9 kW total after power margin) with a 90% duty cycle.

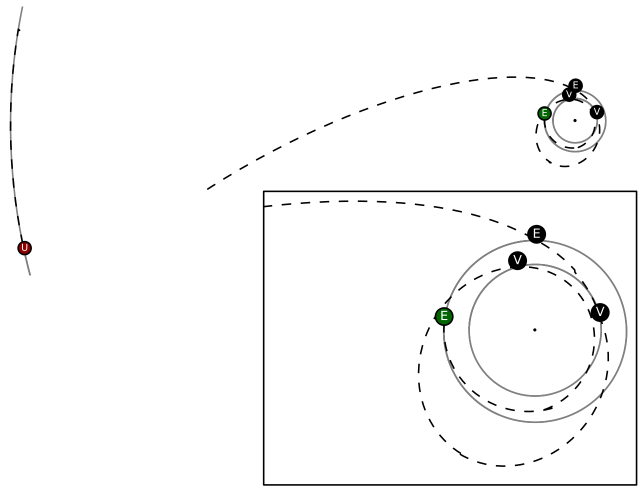

Figure 3. An initial guess for a Uranus trajectory with a Venus-Venus-Earth FB sequence. Dashed lines indicate coast periods.The final optimized solution is shown in Figure 9

Table 3. A summary of various parameters used for the optimization step.

Metric	Value	Note
Power Margin	10%[21]	-
Duty Cycle	90%[21]	-
Propellant Margin	15%[21]	Including 6% for tankage
Arrival V_∞	0 km/s	Rendezvous with final destination
Objective	Max Dry Mass	Compare to 2,560 kg to assess feasibility
Launch Vehicle	AV, DIVH, or SLSB1	Optimize all initial guesses for each
KEP I_{sp}	3,968 s	2 NEXT-C at 4.5 kW each and 90% duty cycle
KEP Thrust	0.280 N	2 NEXT-C at 4.5 kW each and 90% duty cycle

Orbit Insertion

Each interplanetary trajectory arrives at the destination with a V_∞ of 0 km/s, meaning no high-thrust orbit insertion maneuver or aerocapture is required. The same KEP system used to deliver the spacecraft to the destination is also used for a low thrust orbit insertion to two types of orbits: elliptical orbits around the primary body and circular orbits around the largest satellite. To provide a more complete picture of the full mission requirements, this analysis provides estimates for TOF, propellant and ΔV required to deliver a spacecraft to a variety of orbits over a range of final masses.

The low thrust orbit insertion trajectories to elliptical orbits around the primary body are calculated by starting in the orbit of interest, with a chosen spacecraft mass, and propagating backwards in time using 2-body equations of motion until a C_3 of 0 km^2/s^2 (escape) is achieved. Constant thrust in the anti-velocity direction (tangential steering) is assumed throughout the transfer as an approximate minimum time spiral solution. Insertion into circular orbits around satellites are similarly calculated, except two spiral trajectories are required. For the first, the spacecraft begins in a circular orbit around the satellite. Once the spacecraft escapes the satellite, a second spiral trajectory is calculated around the primary body beginning in a circular orbit with semi-major axis equal to that of the satellite orbit. The TOF, propellant and ΔV for the two spirals are then added together to estimate the values for the full transfer.

All transfers are assumed to be planar because the interplanetary trajectory arriving with a V_∞ of 0 km/s would be able to insert into orbit at any inclination. In addition, although the final spiral state has a C_3 of 0 km^2/s^2, the trajectories do not necessarily end at the sphere of influence of the central body as would be assumed by the patched conic approach to the interplanetary solutions. This discrepancy is acceptable for preliminary analysis, but would need to be addressed in further work.

MISSIONS TO URANUS

Results for KEP missions to Uranus are presented in this section. Interplanetary trajectories launching on AV with a TOF of 11-years are the primary focus as those are able to provide adequate dry mass with minimal launch vehicle performance and TOF. A similar set of results using DIVH and SLSB1 can be found in the Appendix, which would enable more delivered mass and additional launch opportunities.

Interplanetary

The following interplanetary trajectory solutions were obtained after optimizing all of the initial guess trajectories. Figure 4 shows the maximum dry mass as a function of launch year for 11-year TOF trajectories launching on AV. The best performing solutions are annotated with their FB sequence and 2, 3, and 4 FB solutions are plotted in blue, red and green, respectively. The top performing sequence is VVE, with dry masses of up to approximately 3,000 kg. This particular solution type, as shown later in Figure 9, exhibits a rather unique VVE sequence in that the 2nd Venus and Earth FB are only separated by 50-60 days. The combination of KEP V_∞ leveraging with 3 rapid FBs results in final Earth departure C_3 (after the final FB) greater than 350 km^2/s^2 in just 1.75 years, while only launching to a C_3 of approximately 16 km^2/s^2. Accumulating so much energy, and therefore traversing vast distances, early in the mission leaves more time to coast before KEP reduces the final destination arrival V_∞ for rendezvous. This solution, however, is dependent upon a particular alignment that does not appear regularly in the solution set. Also of note is that 2 and 3 FB solutions are generally preferable to 4 FB solutions given the constrained TOF.

Figure 5 shows the maximum dry mass as a function of xenon propellant mass for 11-year TOF trajectories launching on AV. The best performing solutions are annotated with their FB sequence and 2, 3, and 4 FB solutions are plotted in blue, red and green, respectively. The best VVE solutions tend to require 1,200 - 1,800 kg of propellant for the interplanetary trajectory. Additional propellant will be needed for any propulsive maneuvers after Uranus arrival.

Figure 6 shows the maximum dry mass as a function of TOF for trajectories launching on AV. The best performing solutions are annotated with their FB sequence and 2, 3, and 4 FB solutions are plotted in blue, red and green, respectively. Interestingly, the VVE FB sequence gives the best performance for all TOFs. A 10-year TOF results in a decrease in dry mass of approximately 400 kg compared to an 11-year TOF. Increasing above 11 years provides approximately 250 kg of dry mass per year up to 13 years.

Finally, Table 4 provides the details on the top 10 yearly solutions found during this broad search. The best VVE solution launches in 2044 to a C_3 of only 11.7 km^2/s^2 and uses 1,639 kg of propellant to deliver a dry mass of 3,011 kg.

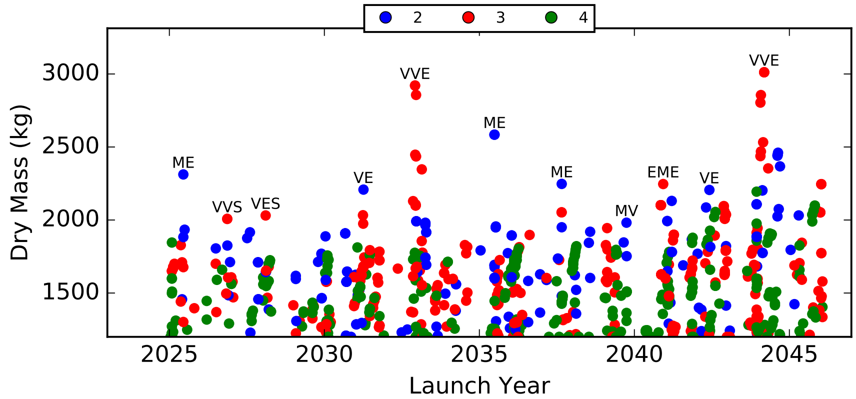

Figure 4. Maximum dry mass across launch dates from 2025 to 2045 for missions to Uranus launching on AV with an 11-year TOF. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

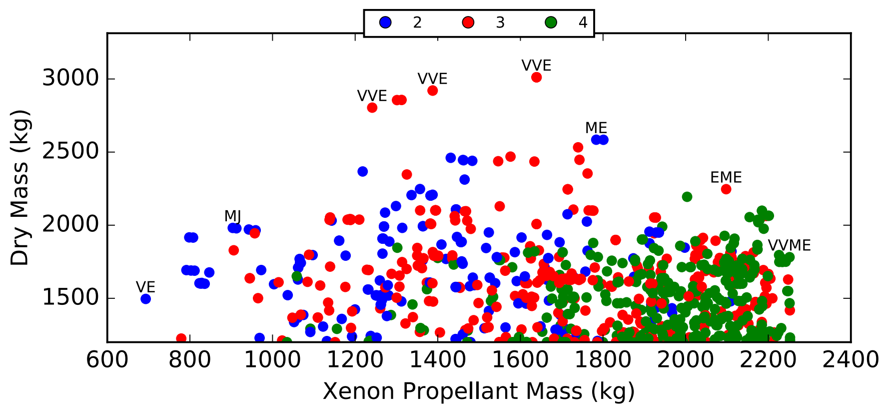

Figure 5. Maximum dry mass as a function of xenon propellant mass for 11-year missions to Uranus launching on AV from 2025-2045. The best performing solutions are annotated with their FB sequence. Solutions with 2, 3, and 4 FBs are colored in blue, red and green, respectively.

Table 4. A sample of the best performing 11-year missions to Uranus launching on AV from 2025-2045.

	Sequence	Launch Date	C_3 (km^2/s^2)	Dry Mass (kg)	Xenon Mass (kg)	TOF (years)
0	ME	6/14/2025	21.7	2312	1464	11.0
1	VE	4/6/2031	24.1	2208	1387	11.0
2	VVE	12/3/2032	15.8	2920	1387	11.0
3	VVE	2/21/2033	23.2	2346	1325	11.0
4	ME	6/29/2035	14.5	2584	1783	11.0
5	ME	8/28/2037	24.0	2247	1356	11.0
6	EME	12/5/2040	14.2	2246	2098	11.0
7	VE	6/2/2042	24.8	2205	1336	11.0
8	VVE	3/9/2044	11.7	3011	1639	11.0
9	VEJ	1/11/2046	19.1	2245	1714	11.0

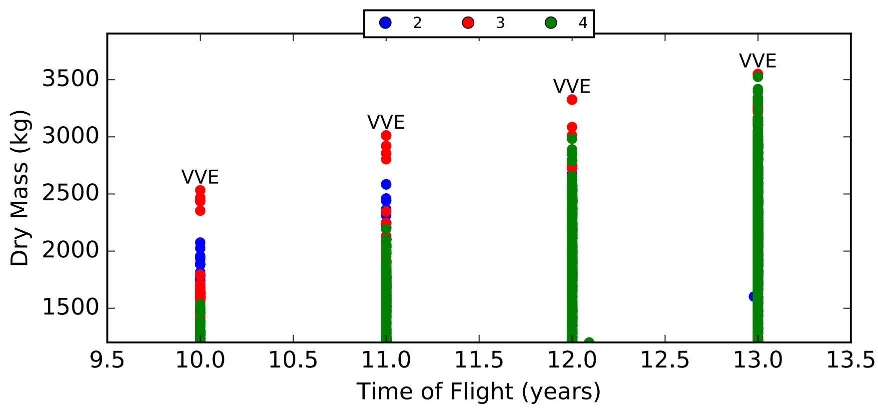

Figure 6. Maximum dry mass as a function of interplanetary TOF for KEP missions to Uranus launching on AV. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

Orbit Insertion

Results for preliminary analysis of low thrust Uranus orbit insertion are shown below. Figure 7 shows orbit insertion trajectories into elliptical orbits with periods of 10, 30, and 60-days and final masses of 2,500, 3,000 and 3,500 kg. A periapsis radius of 1.05 Uranus radii is assumed. Inset into each plotted trajectory is the TOF, propellant mass, and ΔV necessary to complete the transfer. The red star at the beginning of each trajectory represents the point where C_3 is equal to 0. For example, insertion into a 30-day elliptical orbit with a final mass of 3,000 kg would require 266 days, 166 kg of propellant, and 2,096 m/s ΔV. This TOF and propellant mass is in addition to any required for the chosen interplanetary trajectory.

Figure 8 shows contour plots of TOF, propellant mass, and ΔV required to reach a circular orbit around the largest moon of Uranus, Titania. The contours are shown as functions of spacecraft final mass and circular orbit altitude. For example, a 3,000 kg (final mass) spacecraft could reach a 600 km circular orbit around Titania in approximately 400 days with 3.35 km/s ΔV using 270 kg of propellant. This TOF and propellant mass is in addition to any required for the chosen interplanetary trajectory. Due to the relatively low mass of Titania, TOF and propellant mass is primarily dependent upon the final mass of the spacecraft. It is expected that other orbit types (elliptical, multi-body, etc) would require similar TOF and propellant mass since most is spent spiraling down to the Uranus-centered orbit of Titania. A similar trajectory to Oberon, the second largest moon of Uranus, could be completed with even less time and propellant because of it's larger orbital semi-major axis.

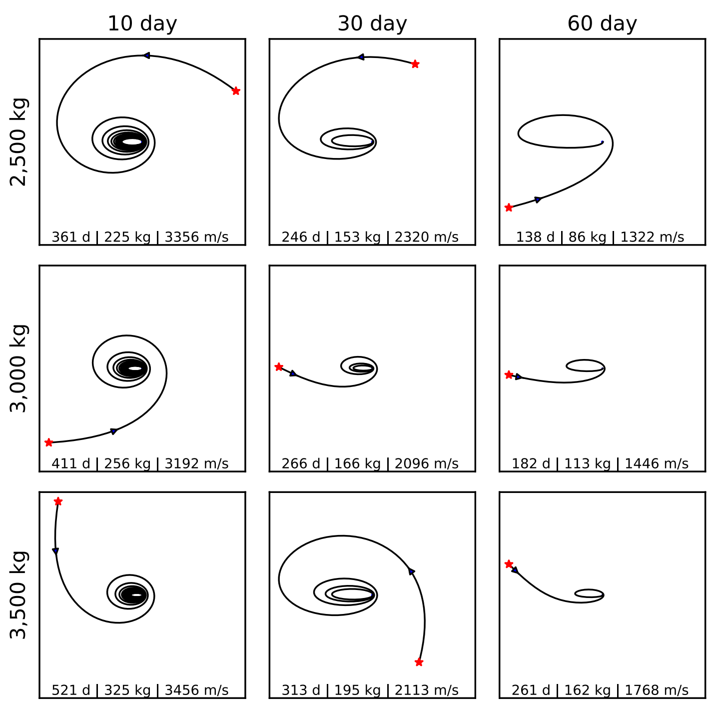

Figure 7. A sample of low thrust orbit insertion trajectories into elliptical orbits with periods of 10 - 60 days and final masses of 2,500 - 3,500 kg. The red star represents the point where C_3 = 0.

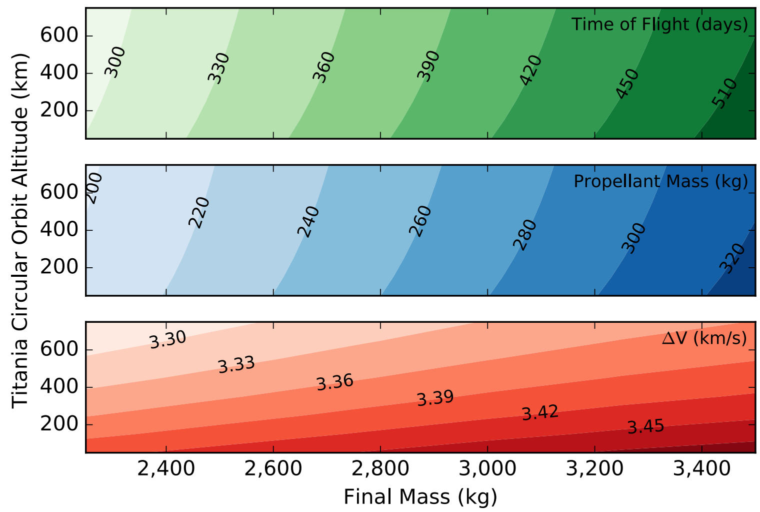

Figure 8. Contour plots of TOF, propellant mass, and ΔV required to reach a circular orbit around the largest moon of Uranus, Titania. Contours are shown as functions of final spacecraft mass and circular orbit altitude.

Example Mission

An example mission can be assembled by combining an interplanetary solution with an orbit insertion trajectory. The best performing interplanetary solution is shown in Figure 9. This solution launches in March 9, 2044 on at AV with a C_3 of 11.7 km^2/s^2 and uses 1,639 kg of xenon and a VVE FB sequence to reach Uranus with an arrival V_∞ of 0 km/s in 11 years. The final mass at Uranus arrival is 3,257 kg, which includes the 15% propellant margin and a dry mass 3,011 kg. This interplanetary dry mass must also include any propellant that is necessary to complete the desired orbit insertion.

The remaining useable propellant ($Xe_{useable}$) for orbit insertion can be calculated using Equation (1), where $Margin_{Xe}$ is the 15% propellant margin, M_{dry} is the 3,011 kg interplanetary dry mass and $M_{s/c}$ is the representative spacecraft mass (minus tankage) of 2,560 kg. The final mass in orbit (M_{orbit}) can be calculated using Equation (2), where M_{final} is the final interplanetary mass of 3,257 kg, and $Xe_{remaining}$ is any remaining useable propellant. Using these equations, the $Xe_{useable}$ is 380 kg and M_{orbit} is 2,875 kg. Using these values (and Figure 7 and Figure 8) a 10-day elliptical Uranus orbit or a 400 km circular Titania orbit could be reached in about 400-days with over 100 kg of useable xenon propellant remaining. The total TOF to reach these orbits would therefore be approximately 12.1 years. Inserting into a 60-day elliptical orbit would save approximately 230 days over the 10-day orbit.

$$Xe_{\text{useable}} = (1 - Margin_{\text{Xe}}) * (M_{\text{dry}} - M_{\text{s/c}}) \tag{1}$$

$$M_{\text{orbit}} = (M_{\text{final}} - M_{\text{s/c}}) + M_{\text{s/c}} + (M_{\text{dry}} - M_{\text{s/c}}) * Margin_{\text{Xe}} + Xe_{\text{remaining}} \tag{2}$$

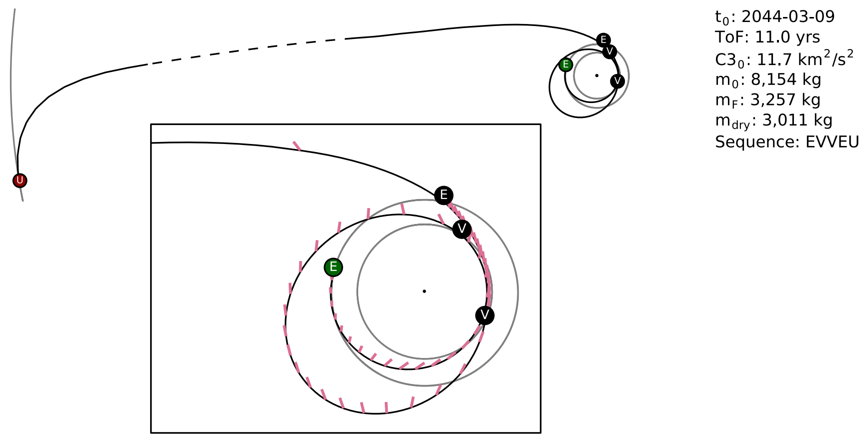

Figure 9. The best performing Uranus trajectory launching on AV with an 11-year TOF. Periods of thrust and coast are plotted with solid and dashed lines, respectively.

MISSIONS TO NEPTUNE

Results for KEP missions to Neptune are presented in this section. Interplanetary trajectories launching on an AV with a TOF of 15-years are the primary focus as those are able to provide adequate dry mass with minimal launch vehicle performance and TOF. A similar set of results using DIVH and SLSB1 can be found in the Appendix, which would enable more delivered mass and additional launch opportunities..

Interplanetary

The following interplanetary trajectory solutions were obtained after optimizing all of the initial guess trajectories. Figure 10 shows the maximum dry mass as a function of launch year for 15-year TOF trajectories launching on AV. The top performing sequence is, again, VVE, with a dry mass of up to approximately 3,000 kg. This particular solution type, as shown later in Figure 15, exhibits the same unique VVE FB sequence discussed previously in the Uranus Interplanetary section. Other high performing sequences include VVEJ, VVVE, and MEMJ. Also of note is that 4 FB solutions represent more of the best performing options than they did for Uranus given the longer TOF constraint.

Figure 11 shows the maximum dry mass as a function of xenon propellant mass for 15-year TOF trajectories launching on AV. The best solutions tend to require 1,400 - 2,500 kg of propellant for the interplanetary trajectory. Additional propellant will be needed for any propulsive maneuvers after Neptune arrival.

Figure 12 shows the maximum dry mass as a function of TOF for trajectories launching on AV. Interestingly, the VVE FB sequence gives the best performance for all TOFs. A 14-year TOF results in a decrease in dry mass of approximately 400 kg compared to an 15-year TOF and a 13-year TOF reduces the maximum dry mass by another 400 kg.

Finally, Table 5 provides the details on the top 10 yearly solutions found during this broad search. The best VVE solution launches in 2037 to a C_3 of only 8.7 km^2/s^2 and uses 1,925 kg of propellant to deliver a dry mass of 2,973 kg.

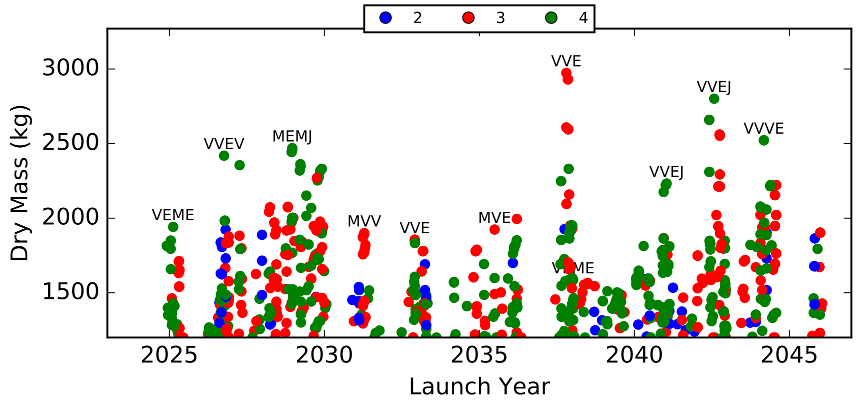

Figure 10. Maximum dry mass across launch dates from 2025 to 2045 for missions to Neptune launching on AV with a 15-year TOF. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

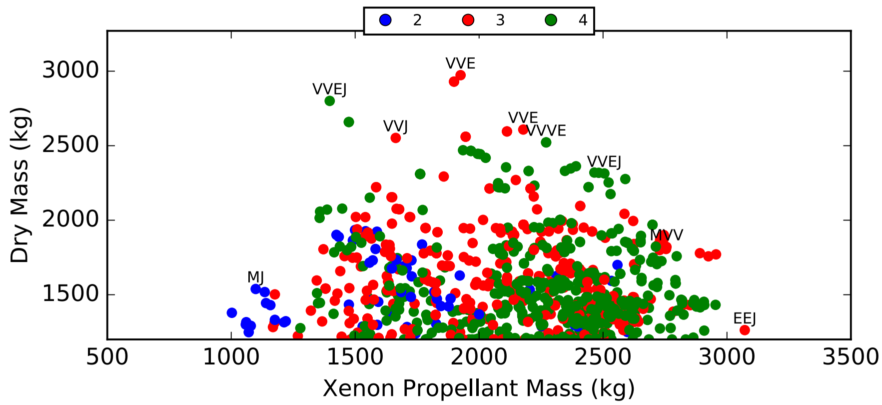

Figure 11. Maximum dry mass as a function of xenon propellant mass for 15-year missions to Neptune launching on AV from 2025-2045. The best performing solutions are annotated with their FB sequence. Solutions with 2, 3, and 4 FBs are colored in blue, red and green, respectively.

Table 5. A sample of the best performing 15-year missions to Neptune launching on AV from 2025-2045.

	Sequence	Launch Date	C_3 (km^2/s^2)	Dry Mass (kg)	Xenon Mass (kg)	TOF (years)
0	VVEV	10/6/2026	13.2	2418	2026	15.0
1	MVVE	4/7/2027	12.9	2355	2108	15.0
2	MEMJ	12/18/2028	13.8	2469	1935	15.0
3	MVEJ	3/23/2029	9.5	2362	2390	15.0
4	VVE	3/17/2036	10.5	1994	2621	15.0
5	VVE	10/21/2037	8.7	2973	1925	15.0
6	VVEJ	12/11/2040	9.8	2175	2530	15.0
7	VVEJ	1/15/2041	12.8	2232	2223	15.0
8	VVEJ	7/29/2042	17.0	2800	1397	15.0
9	VVVE	3/6/2044	9.3	2522	2270	15.0

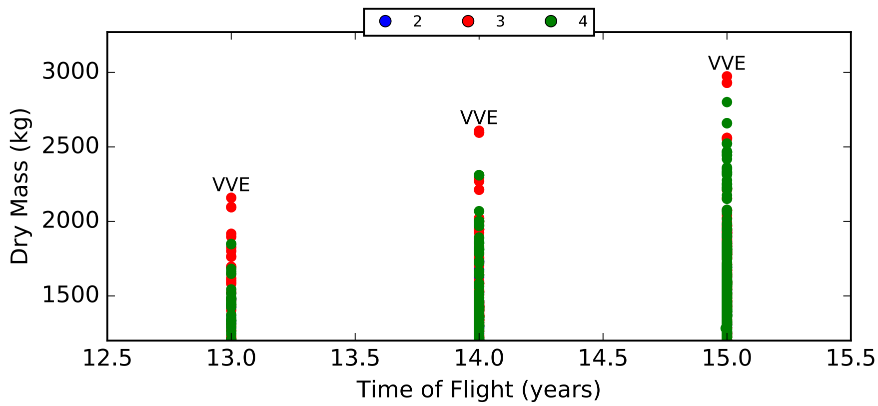

Figure 12. Maximum dry mass as a function of interplanetary TOF for KEP missions to Neptune launching on AV. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

Orbit Insertion

Results for preliminary analysis of low thrust Neptune orbit insertion are shown below. Figure 13 shows orbit insertion trajectories into elliptical orbits with Triton resonances of 3:1, 6:1, and 10:1 (Triton has an orbital period of 5.877 days) and final masses of 2,500, 3,000 and 3,500 kg. A periapsis radius of 1.05 Neptune radii is assumed. Inset into each plotted trajectory is the TOF, propellant mass, and ΔV necessary to complete the transfer. The red star at the beginning of each trajectory represents the point where C_3 is equal to 0. For example, insertion into a 6:1 Triton resonant elliptical orbit with a final mass of 3,000 kg would require 276 days, 172 kg of propellant, and 2,172 m/s ΔV. This TOF and propellant mass is in addition to any required for the interplanetary trajectory.

Figure 14 shows contour plots of TOF, propellant mass, and ΔV required to reach a circular orbit around the largest moon of Neptune, Triton. The contours are shown as functions of spacecraft final mass and circular orbit altitude. For example, a 3,000 kg (final mass) spacecraft could reach a 600 km circular orbit around Triton in approximately 580 days with 4.48 km/s ΔV using 370 kg of propellant. This TOF and propellant mass is in addition to any required for the interplanetary trajectory. TOF and propellant mass are primarily dependent upon the final mass of the spacecraft. It is expected that other orbit types near Triton (elliptical, multi-body, etc) would require similar TOF and propellant mass since most is spent spiraling down to the Neptune-centered orbit of Triton.

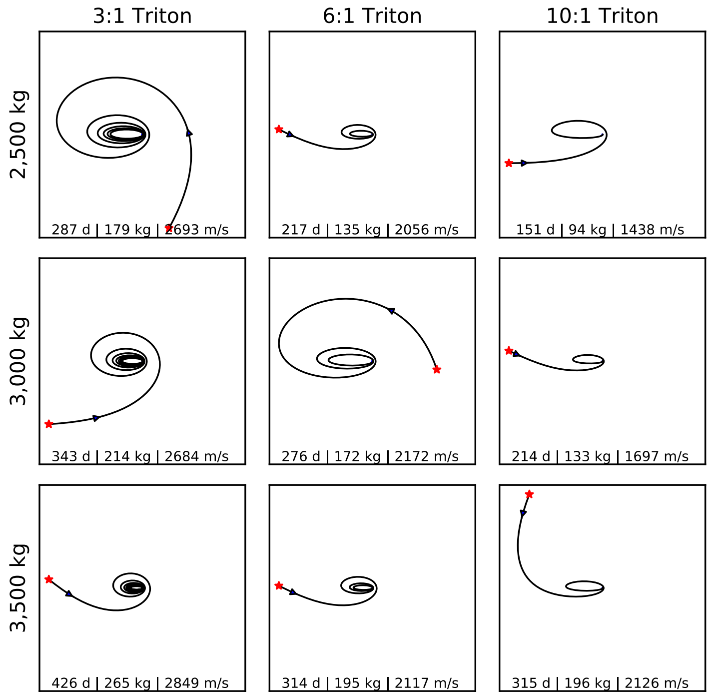

Figure 13. A sample of low thrust orbit insertion trajectories into elliptical orbits with Triton resonances of 3:1, 6:1, and 10:1 and final masses of 2,500 - 3,500 kg. The red star represents the point where C_3 = 0.

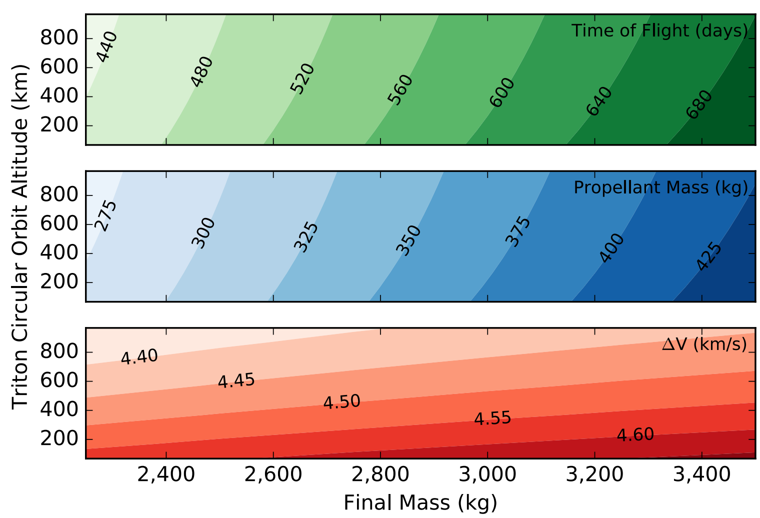

Figure 14. Contour plots of TOF, propellant mass, and ΔV required to reach a circular orbit around the largest moon of Neptune, Triton. Contours are shown as functions of final spacecraft mass and circular orbit altitude.

Example Mission

An example mission can be assembled by combining an interplanetary solution with an orbit insertion trajectory. The best performing interplanetary solution is shown in Figure 15. This solution launches in October 21, 2044 on an AV with a C_3 of 8.7 km^2/s^2 and uses 1,925 kg of xenon and a VVE FB sequence to reach Neptune with an arrival V_∞ of 0 km/s in 15 years. The final mass at Neptune arrival is 3,262 kg, which includes the 15% propellant margin and a dry mass 2,973 kg. This interplanetary dry mass must also include any propellant that is necessary to complete the desired orbit insertion.

The remaining useable propellant ($Xe_{useable}$) for orbit insertion can be calculated using Equation (1). The final mass in orbit (M_{orbit}) can be calculated using Equation (2). The $Xe_{useable}$ is 350 kg and M_{orbit} is 2,911 kg. Using these values (and Figure 13 and Figure 14), a 3:1 Triton resonant orbit could be reach in about 343-days with over 100 kg of useable xenon propellant remaining for a total mission TOF of 16 years. The remaining propellant of 350 kg is slightly less than the estimated 370 kg required to reach a circular Triton orbit in 580 days, for a total mission TOF of 16.6 years. This 20 kg discrepancy in propellant mass is considered to be within the noise of this analysis, so further optimization could lead to a feasible mission. If a circular orbit is not feasible, multi-body orbits may be an attractive alternative requiring less propellant.

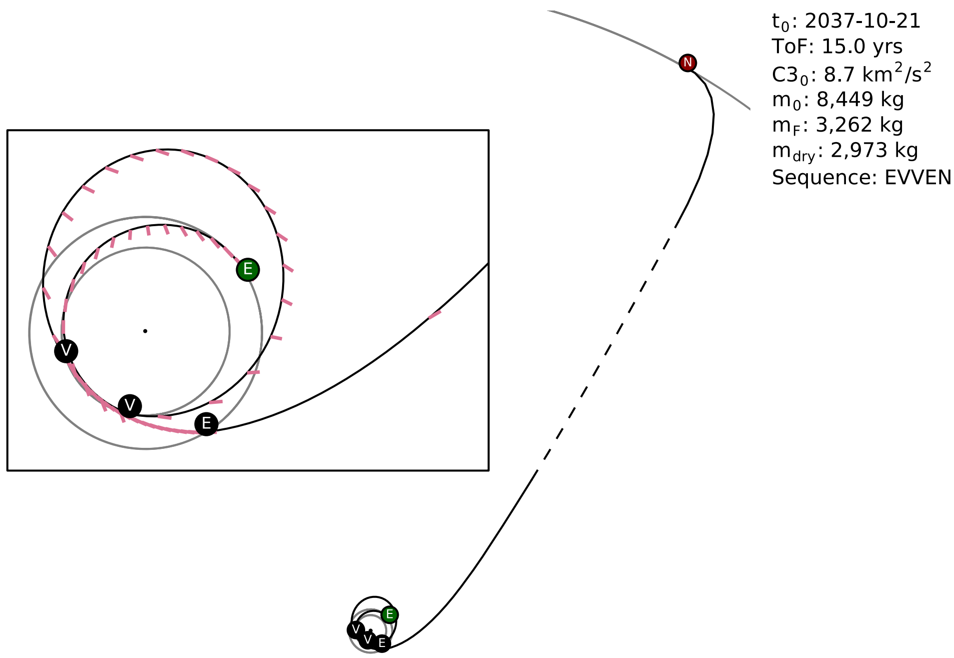

Figure 15. The best performing Neptune trajectory launching on AV with a 15-year TOF. Periods of thrust and coast are plotted with solid and dashed lines, respectively.

MISSIONS TO PLUTO

Results for KEP missions to Pluto are presented in this section. Interplanetary trajectories launching on DIVH with a TOF of 16-years are the primary focus because AV launches did not provide enough mass in 16 years, and SLSB1 did not shown significant increase in delivered mass (suggesting the mission is likely limited by power and TOF, rather than launch vehicle performance). A similar set of results using AV and SLSB1 can be found in the Appendix.

Interplanetary

The following interplanetary trajectory solutions were obtained after optimizing all of the initial guess trajectories. Figure 16 shows the maximum dry mass as a function of launch year for 16-year TOF trajectories launching on DIVH. The top performing sequence is MEJ, with a dry mass of approximately 2,200 kg. Unlike with Uranus and Neptune, nearly all of the top performing trajectories include a Jupiter FB, which limits the mission opportunities to the mid to late 2020's and late-2030's. Other high performing sequences include VEJ and VVEJ. No solutions were found to deliver enough dry mass for the representative KEP spacecraft, even with the SLSB1. This suggests that additional power for KEP or flight time may be necessary to increase the dry mass to an acceptable level. These preliminary results are promising, but more work remains to be done to demonstrate a feasible mission with a TOF of less than 16 years.

Figure 17 shows the maximum dry mass as a function of xenon propellant mass for 16-year TOF trajectories launching on DIVH. The best solutions tend to require 2,500 - 3,000 kg of propellant for the interplanetary trajectory. Additional propellant will be needed for any propulsive maneuvers after Pluto arrival.

Figure 18 shows the maximum dry mass as a function of TOF for trajectories launching on DIVH. Solutions using the MEJ FB sequence give the best performance for both 15 and 16-year TOF, though neither deliver sufficient mass for the representative KEP spacecraft.

Finally, Table 12 provides the details on the top 10 yearly solutions found during this broad search. The best MEJ solution launches in 2026 to a C_3 of 27.9 km^2/s^2 and uses 3,269 kg of propellant to deliver a dry mass of 2,236 kg.

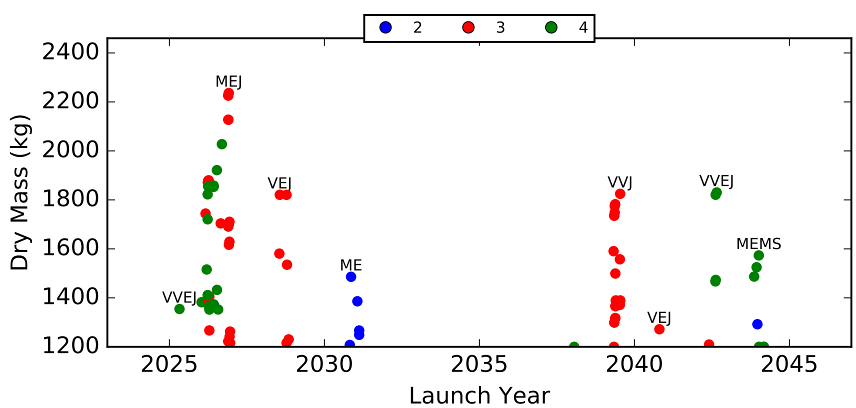

Figure 16. Maximum dry mass across launch dates from 2025 to 2045 for missions to Pluto launching on DIVH with a 16-year TOF. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

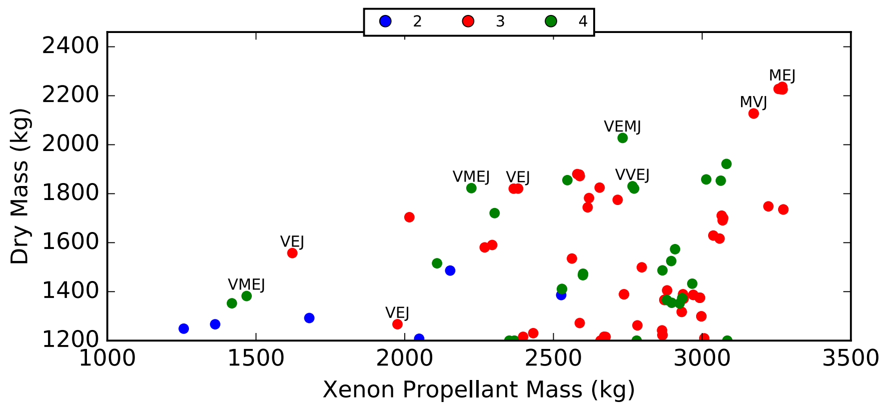

Figure 17. Maximum dry mass as a function of xenon propellant mass for 16-year missions to Pluto launching on DIVH from 2025-2045. The best performing solutions are annotated with their FB sequence. Solutions with 2, 3, and 4 FBs are colored in blue, red and green, respectively.

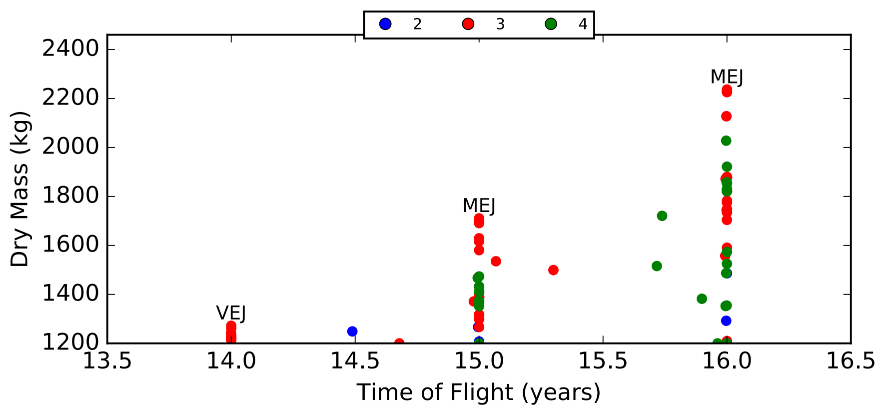

Figure 18. Maximum dry mass as a function of interplanetary TOF for missions to Pluto launching on DIVH. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

Table 6. A sample of the best performing missions to Pluto launching on DIVH from 2025-2045.

	Sequence	Launch Date	C_3 (km^2/s^2)	Dry Mass (kg)	Xenon Mass (kg)	TOF (years)
0	VVEJ	4/30/2025	40.1	1354	2897	16.0
1	MEJ	12/1/2026	27.9	2236	3269	16.0
2	VEJ	7/24/2028	33.6	1820	2381	16.0
3	ME	11/11/2030	48.0	1485	2152	16.0
4	ME	1/24/2031	41.6	1386	2526	15.0
5	VVJ	7/17/2039	38.2	1824	2655	16.0
6	VEJ	10/22/2040	44.8	1271	2588	14.0
7	VVEJ	8/27/2042	26.3	1830	2765	16.0
8	MEMS	12/11/2043	31.2	1524	2895	16.0
9	MEMS	1/6/2044	37.8	1573	2908	16.0

Orbit Insertion

Results for preliminary analysis of low thrust Pluto orbit insertion are shown below. Figure 19 shows orbit insertion trajectories into elliptical orbits with orbit periods of 1, 2 and 6 days and final masses of 2,200, 2,700 and 3,200 kg. A periapsis radius of 1.05 Pluto radii is assumed. Inset into each plotted trajectory is the TOF, propellant mass, and ΔV necessary to complete the transfer. The red star at the beginning of each trajectory represents the point where C_3 is equal to 0. For example, insertion into a 1-day elliptical orbit with a final mass of 2,700 kg would require 39 days, 24 kg of propellant, and 352 m/s ΔV. This TOF and propellant mass is in addition to any required for the chosen interplanetary trajectory.

Figure 20 shows contour plots of TOF, propellant mass, and ΔV required to reach a circular orbit around the largest moon of Neptune, Charon. The contours are shown as functions of spacecraft final mass and circular orbit altitude. For example, a 2,800 kg (final mass) spacecraft could reach a 200 km circular orbit around Charon in approximately 50 days with 0.43 km/s ΔV using 32 kg of propellant. This TOF and propellant mass is in addition to any required for the chosen interplanetary trajectory.

Because Pluto is so much less massive than Uranus and Neptune, KEP provides significantly more maneuverability to explore the Pluto system with relatively little TOF and propellant. The interplanetary portion of the mission is the most challenging aspect. If that can be further optimized along with the KEP spacecraft, exploration of the Pluto system is an exciting possibility.

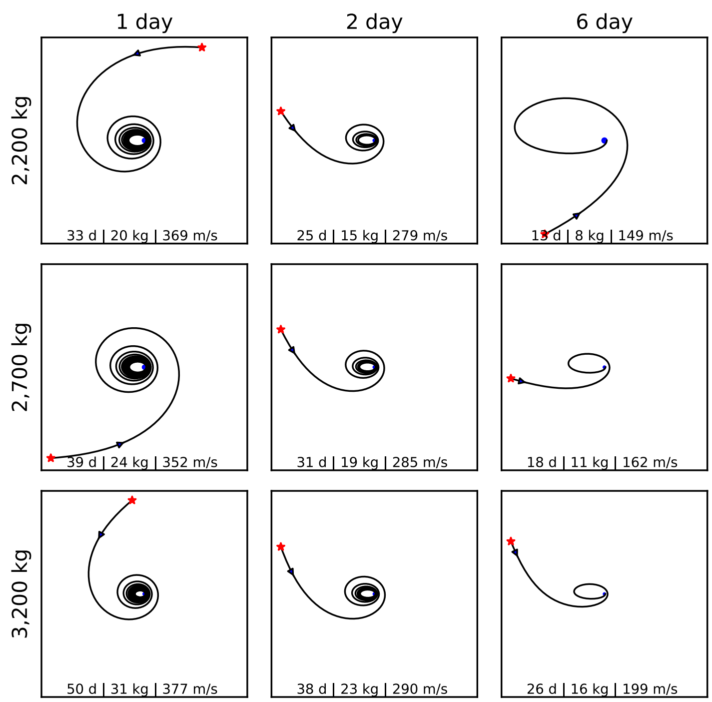

Figure 19. A sample of low thrust orbit insertion trajectories into elliptical orbits with periods of 1-6 days and final masses of 2,200 - 3,200 kg. The red star represents the point where C_3 = 0.

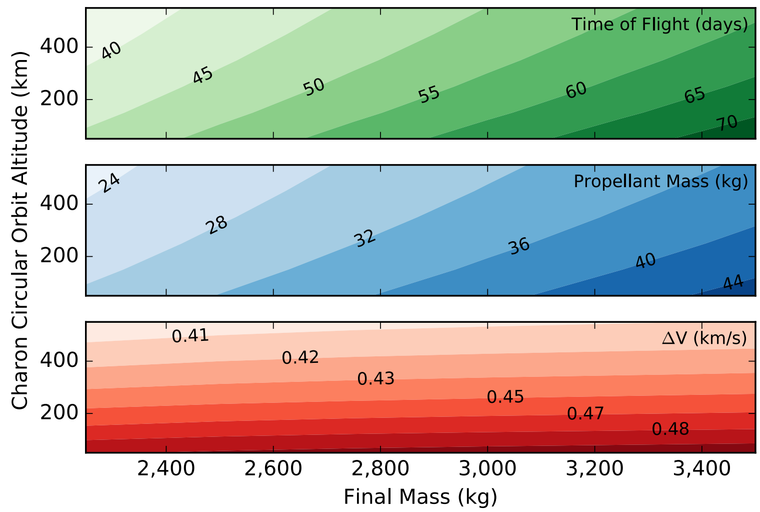

Figure 20. Contour plots of TOF, propellant mass, and ΔV required to reach a circular orbit around the largest moon of Pluto, Charon. Contours are shown as functions of final spacecraft mass and circular orbit altitude.

FUTURE WORK AND CONSIDERATIONS

The results presented in this paper show that KEP is a promising approach to Ice Giant and KBO exploration. With that said, more work remains to be done to further develop these concepts. For Uranus and Neptune, the rapid VVE FB sequence is appealing for KEP missions, but it requires a particular alignment that may not be regularly available. More work should be done to further investigate this sequence because of its remarkable performance. With many missions already shown to be feasible or nearly-feasible, it would also be useful to complete a direct comparison of a KEP mission to a similar chemical propulsion mission.

In addition, a commonly carried payload for Uranus and Neptune mission concepts is an atmospheric probe. This study has not explored how such a probe would be delivered with KEP. Future efforts should explore how KEP may provide unique options for atmospheric probes. Also, this study included preliminary analysis of insertion to generic elliptical orbits, but KEP may enable unique tour designs for exploration of all of the planetary satellites. Further, the preliminary analysis for insertion into satellite centered orbits relied entirely on propulsive maneuvering, but techniques like v-infinity leveraging transfers combined with low thrust spiraling could be used to reduce ΔV and/or TOF.

This study shows that a KEP spacecraft would have significant maneuverability in the Pluto (and other KBO) system if it can be feasibility delivered. Further analysis should be completed to understand how additional KEP power or a different thruster configuration (thrust and specific impulse) may enable such missions. Since nearly-feasible missions were found with the representative spacecraft, perhaps a Pluto-specific spacecraft design could reduce the dry mass by 15% and enable these missions without increasing the power. Another option to increase the delivered dry mass would be to increase TOF.

CONCLUSION

Preliminary analysis shows that KEP could be a feasible approach for orbital exploration of Ice Giants, KBOs, and their moons. A broad search of interplanetary trajectories and preliminary analysis of low thrust orbit insertion trajectories have been completed for Uranus, Neptune and Pluto. For Uranus and Neptune, it was found that high performing interplanetary trajectories exist that launch on medium class launch vehicles (AV) and do not necessarily rely on a Jupiter FB that may limit the mission opportunities. Interplanetary trajectories to Pluto prove to be more challenging, but nearly feasible solutions have been identified. Further investigation and analysis of different spacecraft configurations, such as more power or different specific impulse, may be able to close the feasibility gap for these Pluto missions. Increasing the TOF beyond 16 years may also close the feasibility gap for the Pluto missions, but the authors consider this to be a less appealing option.

Upon arrival to Uranus and Neptune, KEP enables low thrust insertion into elliptical orbits with modest propellant requirements. Further, with additional TOF, KEP can deliver a spacecraft into orbit around the major satellites. The spiral trajectories of either approach could potentially include a robust satellite tour along the way to a final destination - more work remains to be completed in this respect. For missions at Pluto, it was shown that KEP enables significant maneuverability around the relatively low-mass system. Low altitude orbits around Pluto and Charon are possible within weeks of arrival with just 10's of kg of propellant.

Lastly, the unique capability of KEP can be used to resolve some of the major challenges associated with Ice Giant and KBO exploration. Unlike traditional chemical mission concepts, a KEP mission does not require a large orbit insertion maneuver or aerocapture system upon destination arrival. Also, while efficient high-thrust orbit insertion is generally constrained to a small range of inclinations based on the arrival date, a KEP spacecraft could feasibly insert into an orbit at any inclination, regardless of date of arrival, because it arrives at the destination with zero relative velocity. When not used for propulsion, Kilopower could provide increased power to science payloads or be used for communications to enable higher data rates.

ACKNOWLEDGEMENT

The authors thank Jeffrey Pekosh from NASA Glenn Research Center for help in processing the large quantities of data generated in this effort.

APPENDIX: ADDITIONAL URANUS INTERPLANETARY RESULTS

DIVH Solutions

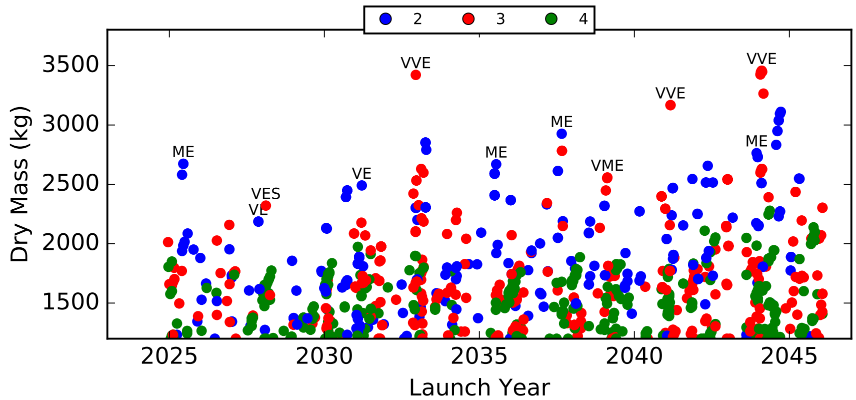

Figure 21. Maximum dry mass across launch dates from 2025 to 2045 for missions to Uranus launching on DIVH with a 11-year TOF. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

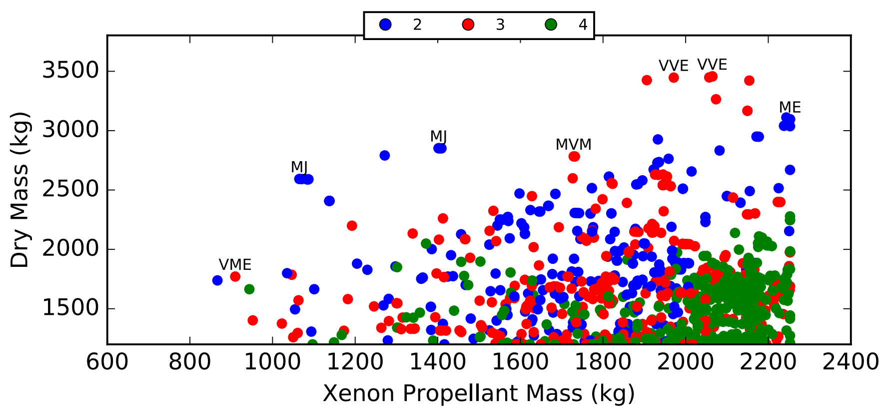

Figure 22. Maximum dry mass as a function of xenon propellant mass for 11-year missions to Uranus launching on DIVH from 2025-2045. The best performing solutions are annotated with their FB sequence. Solutions with 2, 3, and 4 FBs are colored in blue, red and green, respectively.

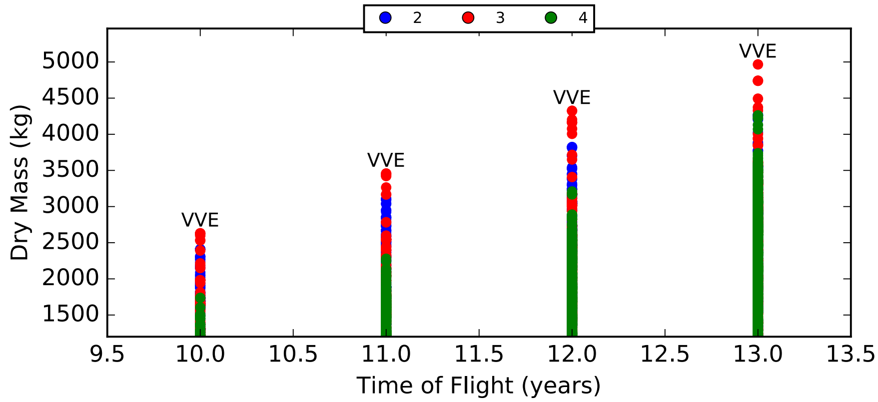

Figure 23. Maximum dry mass as a function of interplanetary TOF for missions to Uranus launching on DIVH. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

Table 7. A sample of the best performing 11-year missions to Uranus launching on DIVH from 2025-2045.

	Sequence	Launch Date	C_3 (km^2/s^2)	Dry Mass (kg)	Xenon Mass (kg)	TOF (years)
0	ME	6/13/2025	38.1	2673	1923	11.0
1	VVE	12/12/2032	28.8	3421	2154	11.0
2	MJ	4/6/2033	42.4	2851	1401	11.0
3	ME	7/18/2035	32.9	2669	2252	11.0
4	ME	8/27/2037	35.5	2926	1932	11.0
5	VME	2/16/2039	40.5	2558	1820	11.0
6	VVE	3/1/2041	31.0	3167	2149	11.0
7	VE	5/14/2042	37.2	2656	2014	11.0
8	ME	12/10/2043	36.8	2763	1958	11.0
9	VVE	2/9/2044	29.3	3456	2064	11.0

SLS Solutions

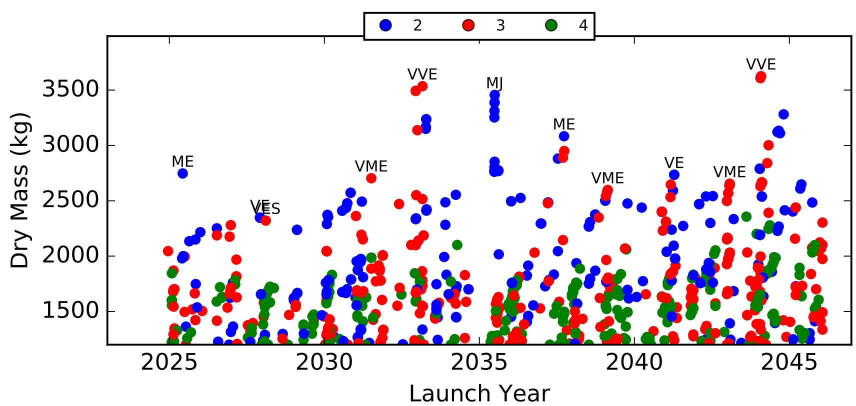

Figure 24. Maximum dry mass across launch dates from 2025 to 2045 for missions to Uranus launching on SLSB1 with a 11-year TOF. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

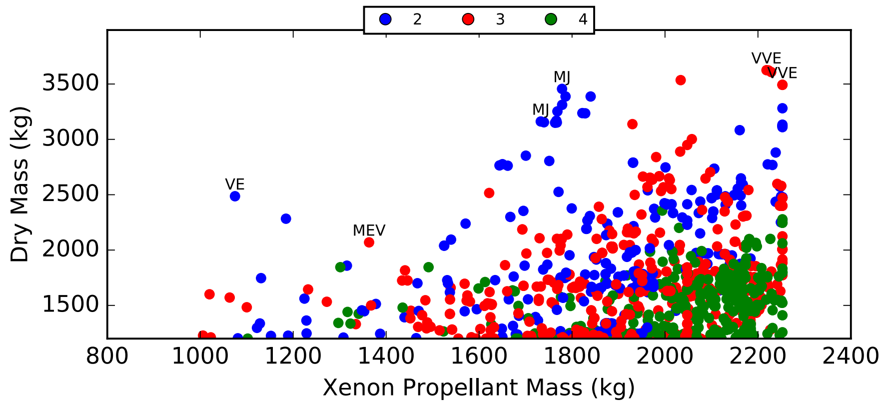

Figure 25. Maximum dry mass as a function of xenon propellant mass for 11-year missions to Uranus launching on SLSB1 from 2025-2045. The best performing solutions are annotated with their FB sequence. Solutions with 2, 3, and 4 FBs are colored in blue, red and green, respectively.

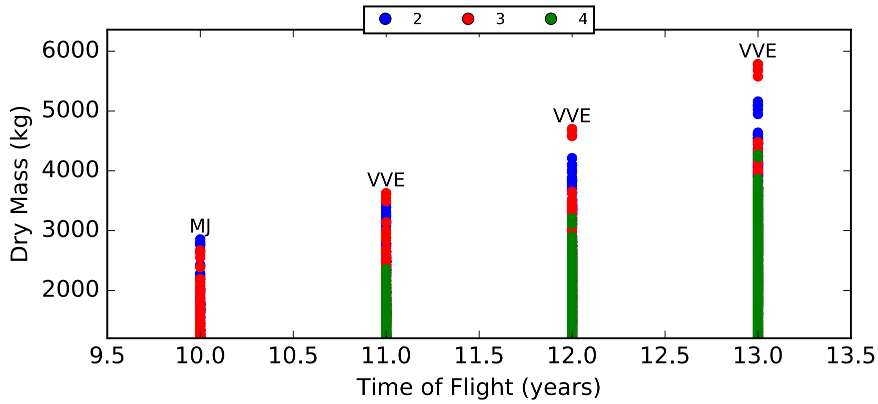

Figure 26. Maximum dry mass as a function of interplanetary TOF for missions to Uranus launching on SLSB1. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

Table 8. A sample of the best performing 11-year missions to Uranus launching on SLSB1 from 2025-2045.

	Sequence	Launch Date	C_3 (km^2/s^2)	Dry Mass (kg)	Xenon Mass (kg)	TOF (years)
0	ME	6/6/2025	70.0	2746	2001	11.0
1	VME	7/7/2031	69.4	2703	2097	11.0
2	VVE	12/11/2032	61.8	3492	2252	11.0
3	VVE	3/1/2033	62.3	3535	2033	11.0
4	MJ	6/30/2035	61.6	3456	1778	11.0
5	ME	9/24/2037	65.7	3083	2160	11.0
6	VE	4/14/2041	69.1	2735	2105	11.0
7	VME	1/28/2043	71.1	2652	1967	11.0
8	VVE	2/2/2044	61.1	3625	2218	11.0
9	VE	5/21/2045	69.2	2647	2163	11.0

APPENDIX: ADDITIONAL NEPTUNE INTERPLANETARY RESULTS

DIVH Solutions

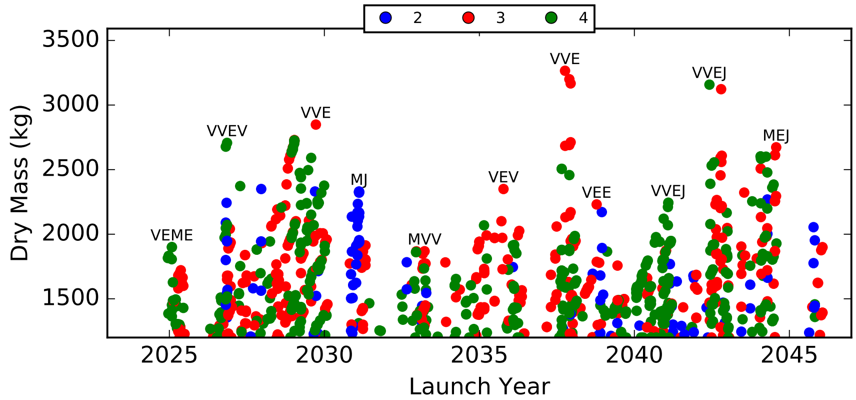

Figure 27. Maximum dry mass across launch dates from 2025 to 2045 for missions to Neptune launching on DIVH with a 15-year TOF. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

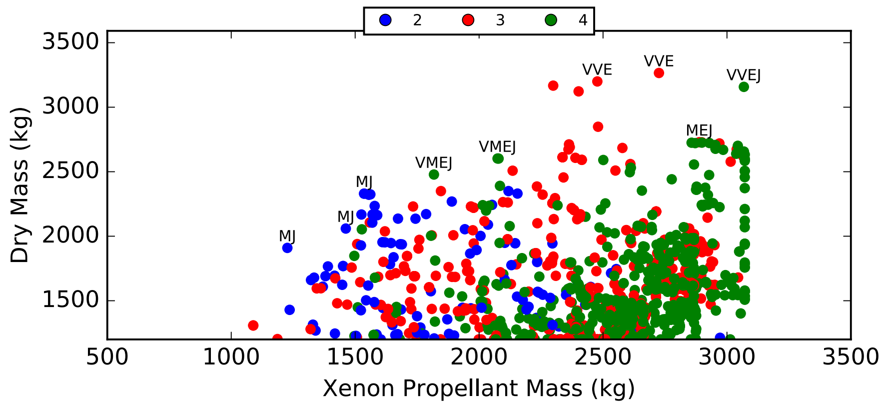

Figure 28. Maximum dry mass as a function of xenon propellant mass for 15-year missions to Neptune launching on DIVH from 2025-2045. The best performing solutions are annotated with their FB sequence. Solutions with 2, 3, and 4 FBs are colored in blue, red and green, respectively.

Table 9. A sample of the best performing 15-year missions to Neptune launching on DIVH from 2025-2045.

	Sequence	Launch Date	C_3 (km^2/s^2)	Dry Mass (kg)	Xenon Mass (kg)	TOF (years)
0	VVEV	11/11/2026	27.0	2707	2953	15.0
1	MVVE	4/15/2027	28.7	2372	3071	15.0
2	MEJ	12/26/2028	20.4	2673	3039	15.0
3	VVE	9/22/2029	30.5	2848	2479	15.0
4	MJ	2/13/2031	46.4	2330	1536	15.0
5	VEV	10/12/2035	42.3	2349	1845	15.0
6	VVE	10/5/2037	24.6	3265	2725	15.0
7	VVEJ	6/3/2042	22.4	3157	3068	15.0
8	MEJ	7/18/2043	37.8	2322	2256	14.0
9	MEJ	7/29/2044	33.3	2672	2360	15.0

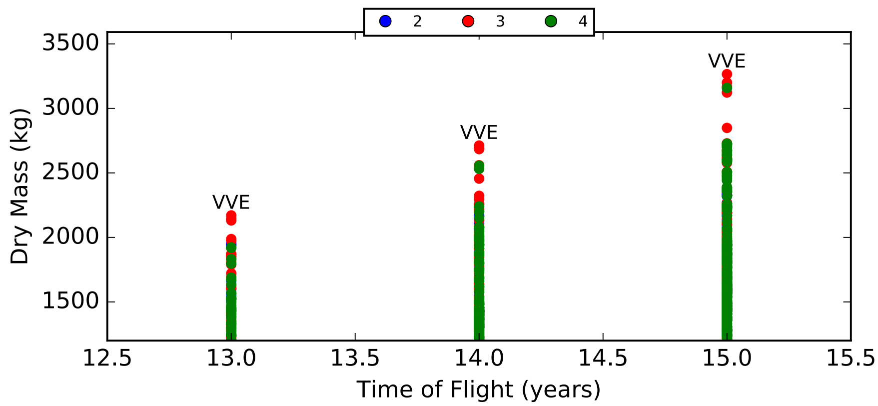

Figure 29. Maximum dry mass as a function of interplanetary TOF for missions to Neptune launching on DIVH. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

SLS Solutions

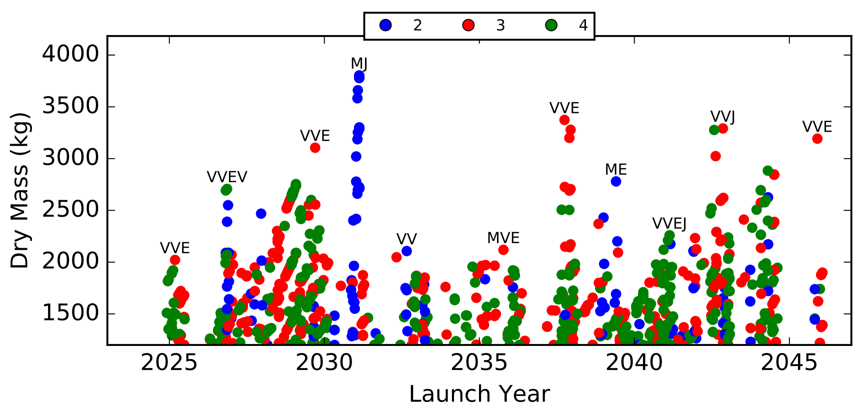

Figure 30. Maximum dry mass across launch dates from 2025 to 2045 for missions to Neptune launching on SLSB1 with a 15-year TOF. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

Table 10. A sample of the best performing 15-year missions to Neptune launching on SLSB1 from 2025-2045.

	Sequence	Launch Date	C_3 (km^2/s^2)	Dry Mass (kg)	Xenon Mass (kg)	TOF (years)
0	VVEV	11/11/2026	28.6	2707	2953	15.0
1	MEMJ	12/26/2028	27.1	2682	2909	15.0
2	VVE	9/13/2029	61.6	3105	2615	15.0
3	MJ	2/15/2031	59.5	3803	2257	15.0
4	VVE	9/30/2037	57.4	3373	2890	15.0
5	ME	5/30/2039	62.4	2779	2804	15.0
6	VVJ	11/9/2042	57.0	3291	3020	15.0
7	VVVE	12/11/2043	51.4	2506	3049	15.0
8	VMEJ	4/21/2044	63.5	2883	2585	15.0
9	VVE	11/26/2045	15.1	3192	2637	15.0

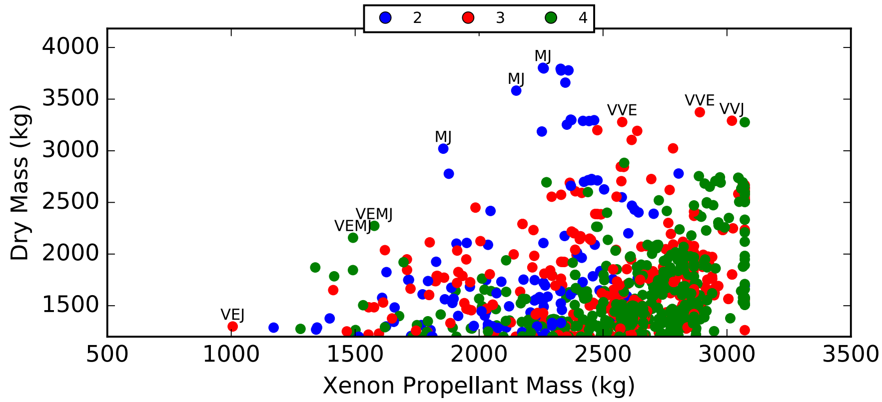

Figure 31. Maximum dry mass as a function of xenon propellant mass for 15-year missions to Neptune launching on SLSB1 from 2025-2045. The best performing solutions are annotated with their FB sequence. Solutions with 2, 3, and 4 FBs are colored in blue, red and green, respectively.

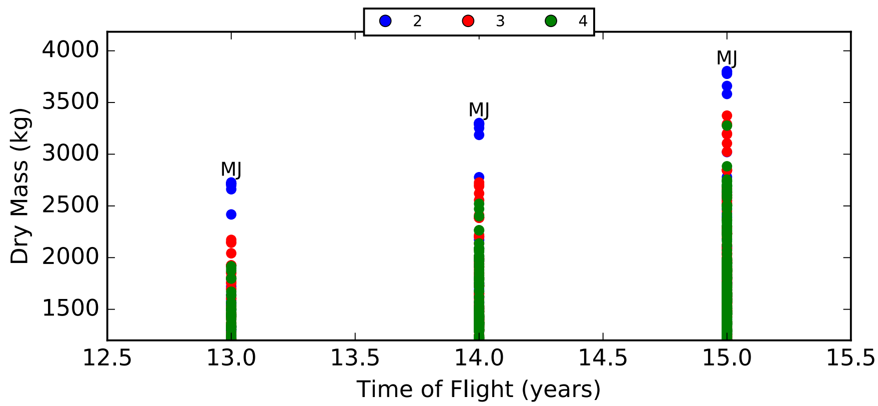

Figure 32. Maximum dry mass as a function of interplanetary TOF for missions to Neptune launching on SLSB1. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

APPENDIX: ADDITIONAL PLUTO INTERPLANETARY RESULTS

AV Solutions

Table 11. A sample of the best performing 16-year missions to Pluto launching on AV from 2025-2045.

	Sequence	Launch Date	C_3 (km^2/s^2)	Dry Mass (kg)	Xenon Mass (kg)	TOF (years)
0	VVEJ	4/15/2025	23.2	1312	2227	16.0
1	MEJ	11/14/2026	18.7	1944	2007	16.0
2	MVEJ	3/31/2027	12.5	1771	2654	16.0
3	MEJ	12/18/2028	15.3	1969	2254	16.0
4	ME	11/11/2030	33.8	1200	1633	15.9
5	ME	1/25/2031	20.5	1586	2182	15.9
6	MEEJ	3/31/2038	19.2	1336	2499	16.0
7	VEJ	6/3/2039	21.7	1702	1995	16.0
8	VVEJ	8/28/2042	12.4	1829	2609	16.0
9	MEMS	12/6/2043	16.9	1559	2478	16.0

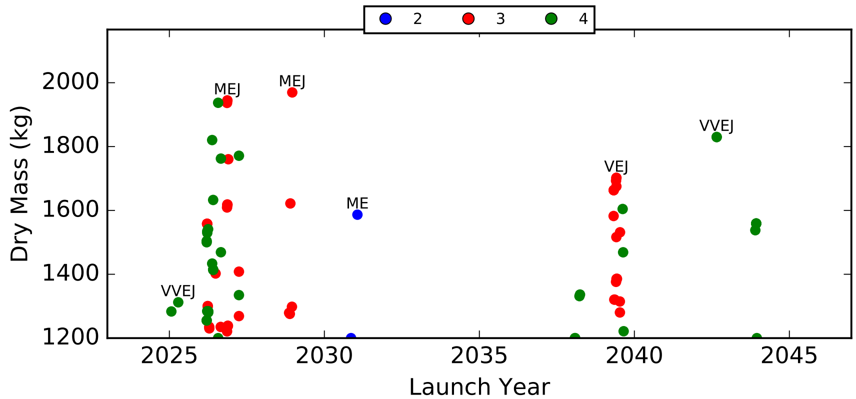

Figure 33. Maximum dry mass across launch dates from 2025 to 2045 for missions to Pluto launching on AV with a 16-year TOF. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

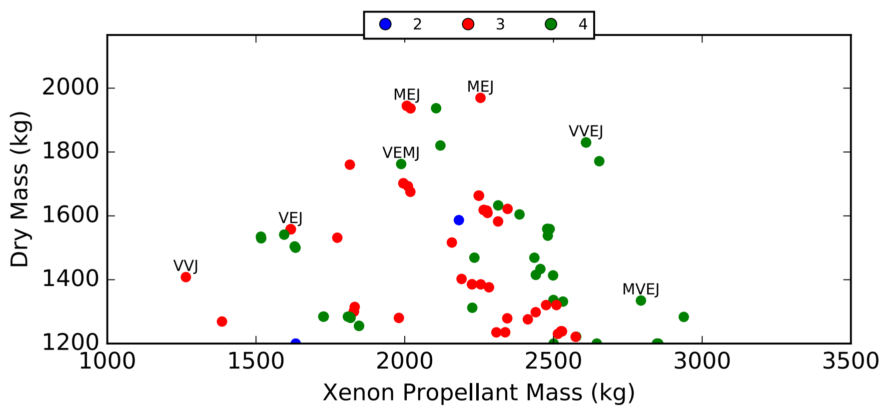

Figure 34. Maximum dry mass as a function of xenon propellant mass for 16-year missions to Pluto launching on AV from 2025-2045. The best performing solutions are annotated with their FB sequence. Solutions with 2, 3, and 4 FBs are colored in blue, red and green, respectively.

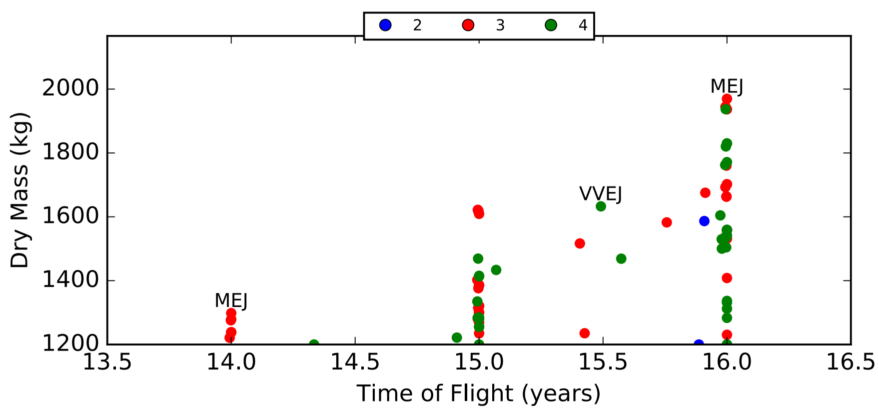

Figure 35. Maximum dry mass as a function of interplanetary TOF for KEP missions to Pluto launching on AV. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

SLS Solutions

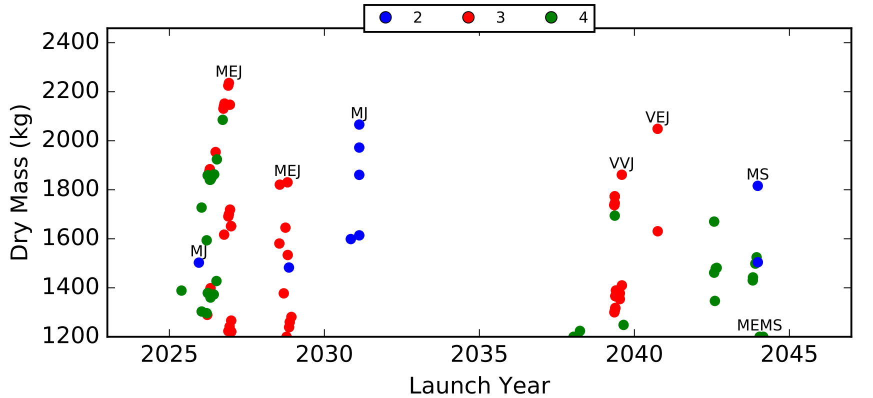

Figure 36. Maximum dry mass across launch dates from 2025 to 2045 for missions to Pluto launching on SLSB1 with a 16-year TOF. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

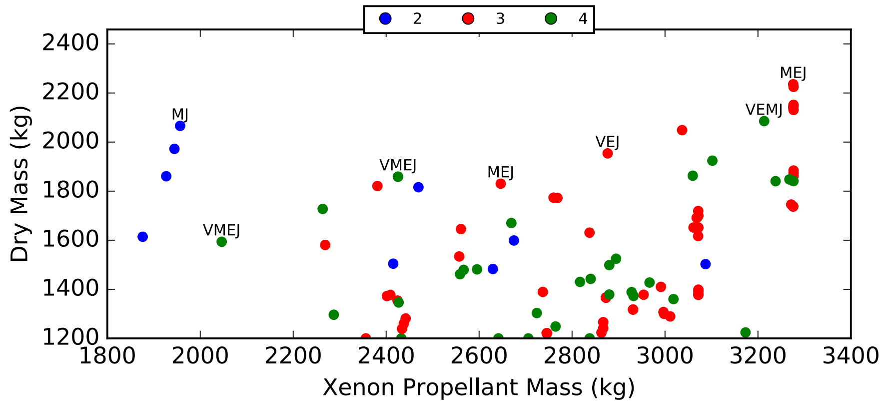

Figure 37. Maximum dry mass as a function of xenon propellant mass for 16-year missions to Pluto launching on SLSB1 from 2025-2045. The best performing solutions are annotated with their FB sequence. Solutions with 2, 3, and 4 FBs are colored in blue, red and green, respectively.

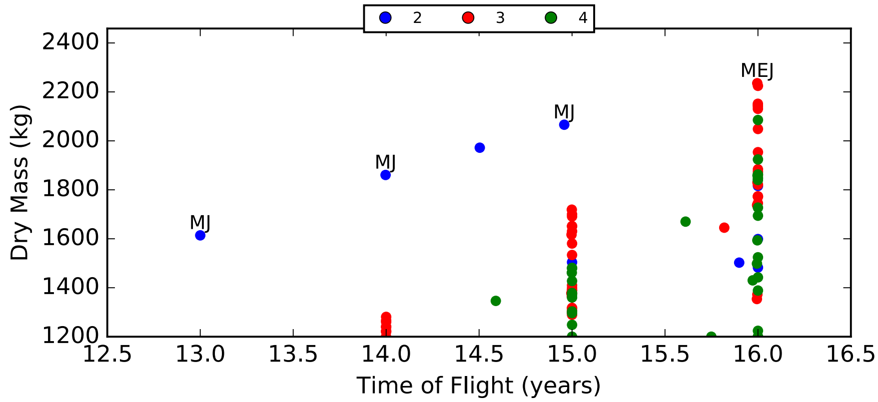

Figure 38. Maximum dry mass as a function of interplanetary TOF for KEP missions to Pluto launching on SLSB1. The best performing solutions are annotated with their FB sequence. 2, 3, and 4 FB solutions are colored in blue, red and green, respectively.

Table 12. A sample of the best performing 16-year missions to Pluto launching on SLSB1 from 2025-2045.

	Sequence	Launch Date	C_3 (km^2/s^2)	Dry Mass (kg)	Xenon Mass (kg)	TOF (years)
0	MJ	12/13/2025	63.2	1502	3087	15.9
1	MEJ	12/2/2026	35.8	2235	3275	16.0
2	MEJ	10/22/2028	43.5	1830	2646	16.0
3	ME	11/7/2030	73.2	1598	2674	16.0
4	MJ	2/15/2031	76.4	2065	1956	15.0
5	MVVJ	3/31/2038	50.4	1224	3173	16.0
6	VVJ	8/5/2039	61.8	1861	3276	16.0
7	VEJ	9/30/2040	65.9	2048	3036	16.0
8	VVEJ	7/29/2042	72.6	1670	2669	15.6
9	MS	12/24/2043	73.4	1815	2469	16.0

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