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John W. Sarappo III
jsarappo@vols.utk.edu

Samuel Brickley
sbrickle@vols.utk.edu

Iliane Domenech
idomenec@vols.utk.edu

Lorenzo Franceschetti
lfrances@vols.utk.edu

James E. Lyne
University of Tennessee, Knoxville

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INVESTIGATION OF INTERPLANETARY TRAJECTORIES TO SEDNA

**Samuel Brickley*, Iliane Domenech*, Lorenzo Franceschetti*, John Sarappo*,
and James Evans Lyne†**

This study aims to explore various orbital trajectories to reach the trans-Neptunian object Sedna. In addition to the opportunity to observe Sedna's physical properties such as surface composition and atmosphere, such a mission may yield insight into the early history of the Solar System, due to the remoteness of trans-Neptunian objects. We compare trajectories by their C_3 values, transit times, arrival speeds, Jupiter flyby distances, and Jupiter radiation dosages. The possibility of an orbital capture or lander mission is also considered.

INTRODUCTION

In 2003, the trans-Neptunian object (TNO) Sedna was discovered. Its orbit is far beyond that of Neptune and highly eccentric, with a perihelion of approximately 76 AU and an aphelion of 937 AU. Since Sedna will reach its perihelion in 2076 [2, 3], a mission in the next few decades would allow for a relatively low transit time. In this study, we explore the optimal launch windows for a departure from Earth to Sedna by comparing the characteristic energy required at departure, C_3, for various orbital maneuvers. In addition, we compare trajectories relying only on a Jupiter flyby, and trajectories also employing a delta V Earth gravity assist (ΔVEGA) maneuver. Shorter transit times to Sedna typically require closer Jupiter flybys, with the potential for damage to the spacecraft caused by the intense Jovian radiation belts. Therefore, we also compare candidate trajectories with regard to their flyby radiation doses.

Previous work by Zubko et al. has explored the potential for very fast trajectories to Sedna, including transit times as low as around 12 years [4, 5]. Our group has previously examined a wide range of TNO missions [6, 7], including a handful of Earth - Jupiter - Sedna trajectories. In this study, we also extend that work to examine the feasibility of orbital capture or lander missions using currently available or soon-to-be available, American launch vehicles.

METHODOLOGY

In our analyses, the software MAnE (Mission Analysis Environment) was employed to explore various trajectories to Sedna and to study their important characteristics. NASA's Launch Service Program Performance Website [8] was used to estimate potential mass on target to Sedna, for a variety of standard launch vehicles. In order to estimate Jupiter flyby radiation doses, we employed the tools developed by Stewart [9].

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*: Student, Department of Mechanical, Aerospace & Biomedical Engineering, University of Tennessee, Knoxville, Tennessee, 37996.

†: Clinical Associate Professor and Corresponding Author, jelyne@utk.edu, Department of Mechanical, Aerospace & Biomedical Engineering,University of Tennessee, Knoxville, Tennessee, 37996.

ANALYSIS AND RESULTS

A. Launch windows

Figure 1 shows the launch windows determined over the span of 25 years for both a direct approach to Sedna and one involving a Jupiter gravity assist (JGA). Importantly, the required C_3 is smaller for Earth – JGA – Sedna trajectories as a result of the energy gained during the Jupiter gravity assist (JGA). Because of their very high departure energies, direct Earth to Sedna trajectories are impractical and are not considered in this study.

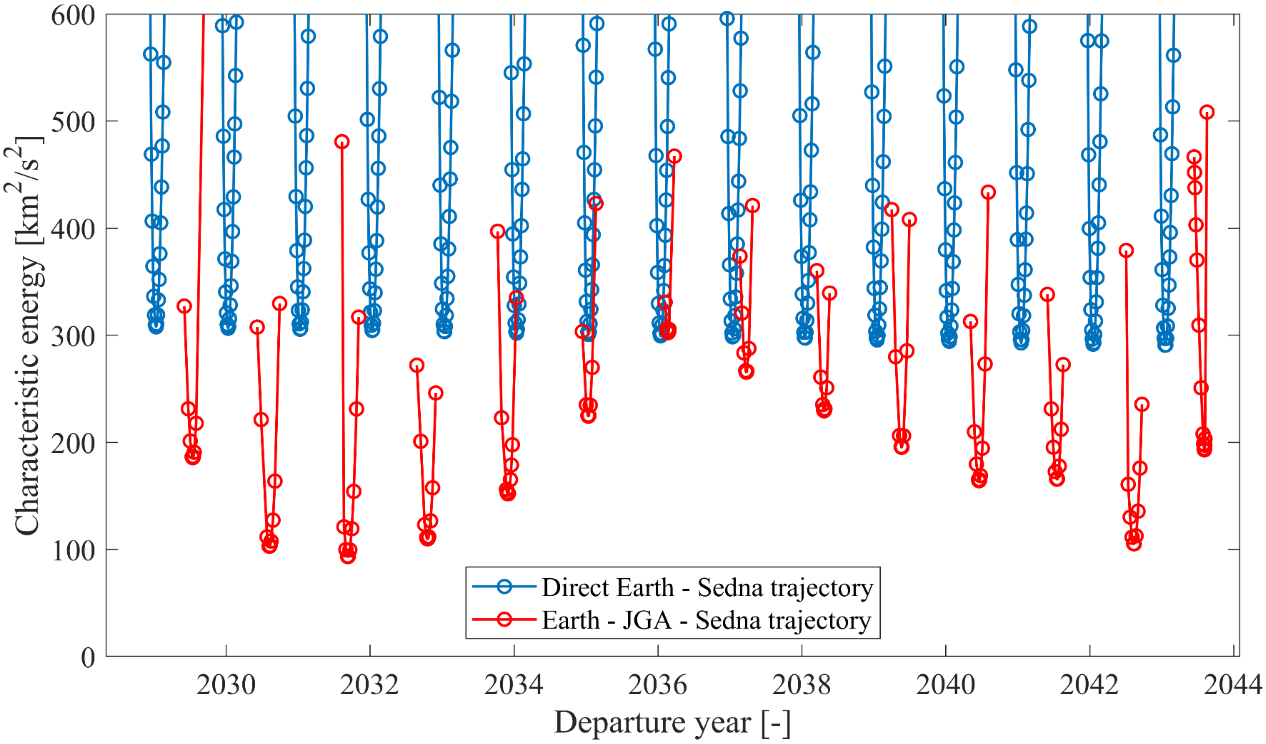

Figure 1 Departure launch windows for both direct Earth to Sedna trajectories and the same trajectory including a JGA, for a transit time of 40 years.

Figure 1 shows that at some point every year, the ideal departure date for a direct flight to Sedna occurs only as a result of Earth's position with respect to the Sun, and Sedna's position at arrival (after 40 years). Importantly, the required C_3 hardly changes yearly even over a span of 25 years, probably due to Sedna's large hyperbolic orbit. Meanwhile, the optimal opportunity to perform an efficient JGA assist will only occur every 12 years as a result of Jupiter's 12-year orbit. Direct Earth to Sedna opportunities occur once a year (the synodic period of Earth and Sedna), while JGA opportunities take place on a twelve-year cycle and afford much lower Earth departure energies.

B. Earth – JGA – Sedna trajectory

As Fig. 1 shows, the earliest opportunity for a JGA trajectory occurs from 2030 to 2034, with the optimal date being in March of 2032. Figure 2 shows a sample trajectory for an Earth – JGA – Sedna trajectory.

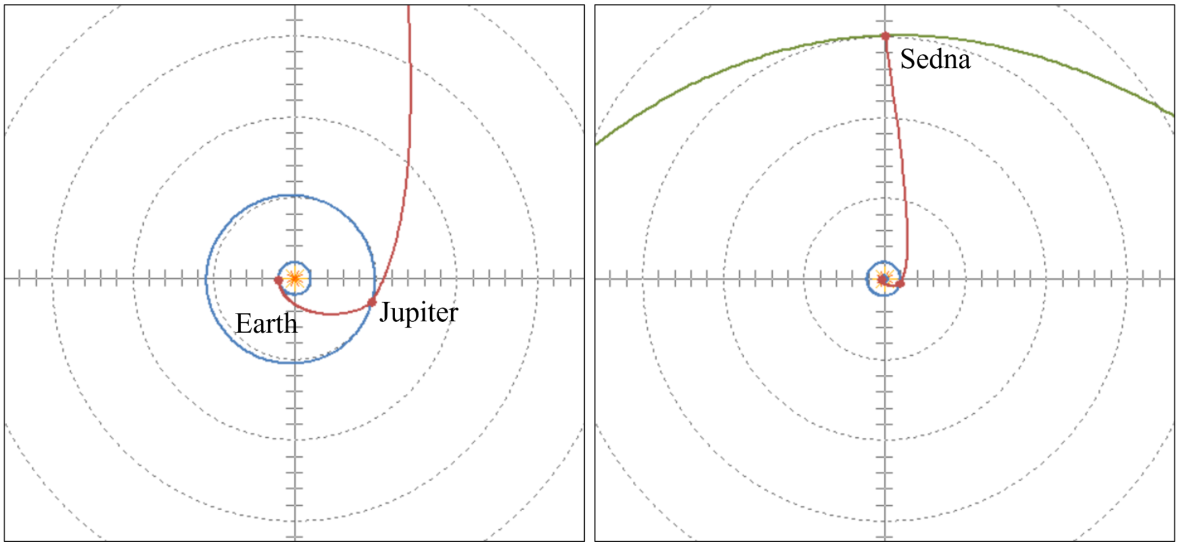

Figure 2 Earth – JGA – Sedna trajectory showing (left), the Jupiter swingby from Earth and (right), the approach to Sedna.

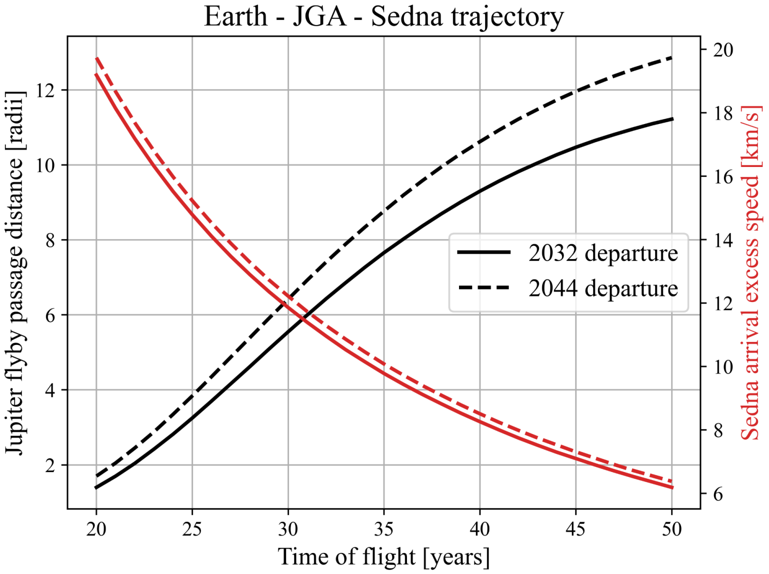

Figure 3 Earth – JGA – Sedna trajectory comparing the arrival excess speed and Jupiter flyby distances for two departure dates against the transit time.

Figure 3 shows that, consistently, with increasing transit times the speed of arrival at Sedna decreases. Meanwhile, the passage distance to Jupiter increases, reducing radiation risks. For departure in 2044, the Jupiter passage distance is larger than for departure in 2032; however, the excess speed is increased. In Fig. 4, the characteristic energy is plotted against the time of flight for both departure years, showing the decreased energy requirements at higher transit times, though this eventually reaches a minimum. The 2032 departure suggests lower energy requirements, which correlates to a smaller total ΔV for the trajectory.

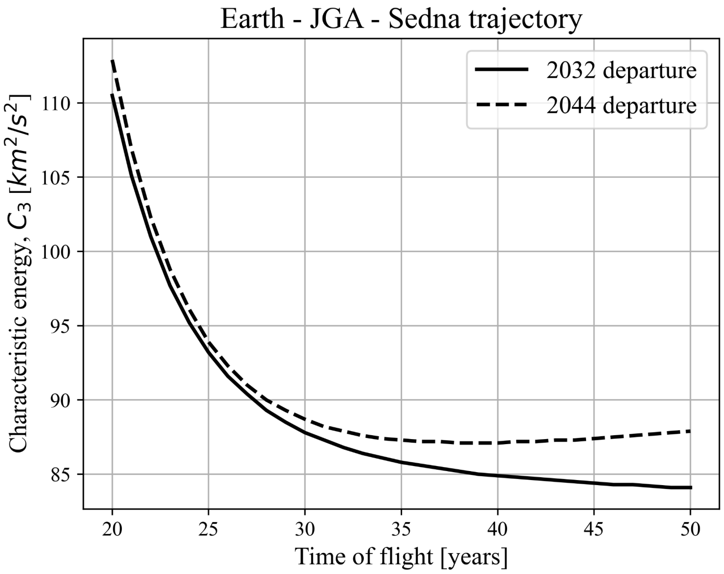

Figure 4 Earth – JGA – Sedna trajectory comparing the departure energy requirements for two departure dates against the transit time.

C. Earth – ΔVEGA – JGA – Sedna trajectory

In order to further increase the performance of the transit to Sedna, a ΔVEGA maneuver is explored as an addition to the previous mission in (B). The ΔVEGA maneuver adds a gravity assist at Earth to extract additional energy. Since the ΔVEGA lasts a couple of years, a departure from Earth traditionally happens slightly behind the Jupiter launch windows in Fig. 1, and this launch window is presented in Fig. 5. Figure 6 shows a sample trajectory with a ΔVEGA with Earth departure in 2030, while Fig. 7 compares parameters for two different departure years.

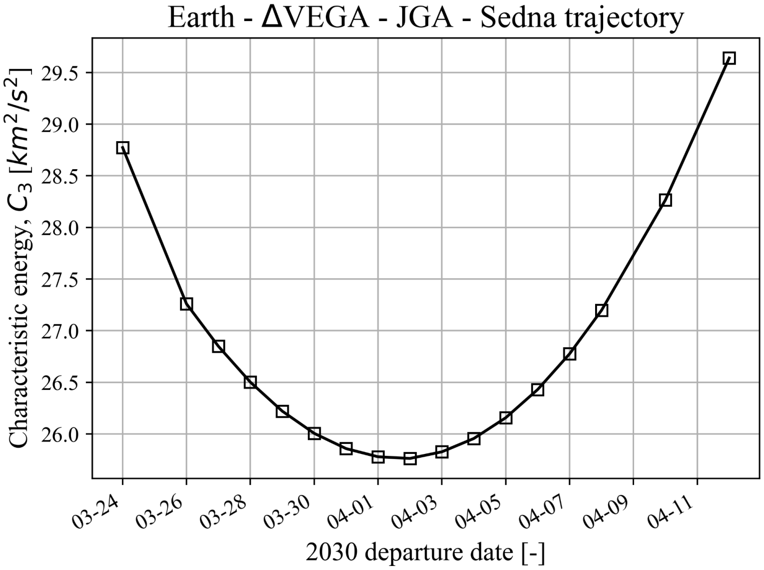

Figure 5 Departure launch window for the Earth – ΔVEGA – JGA – Sedna trajectory for a TOF of 40 years.

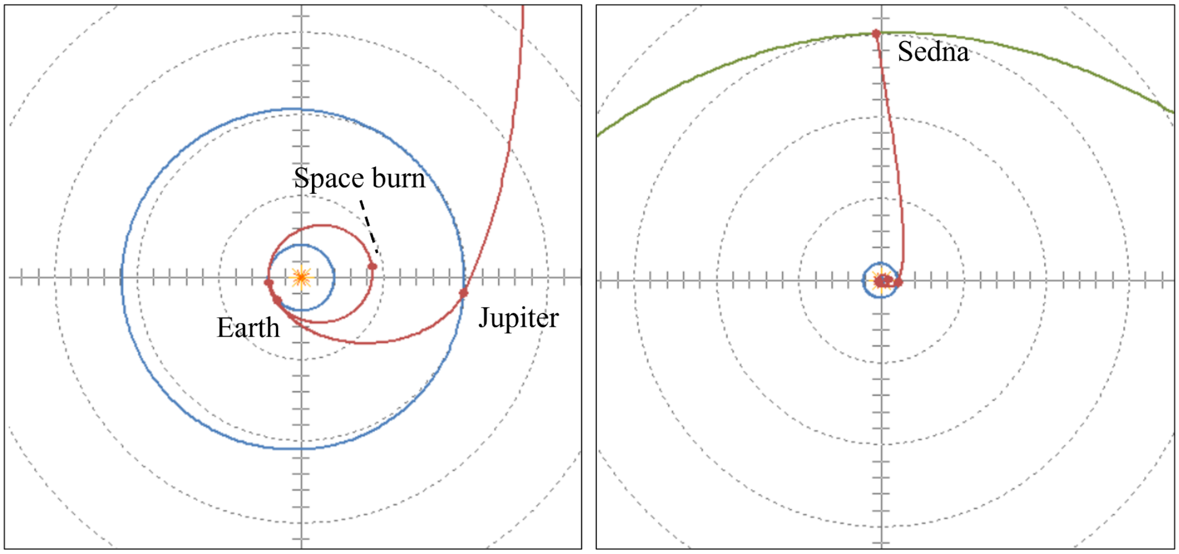

Figure 6 **Earth – ΔVEGA – JGA – Sedna trajectory showing (left), the ΔVEGA and Jupiter swingby from Earth, and (right), the approach to Sedna.**

Figure 7 shows, by comparison to JGA-only transits, that the ΔVEGA is a favorable addition for trajectories to Sedna by increasing the passage distance of Jupiter and decreasing the arrival excess speed.

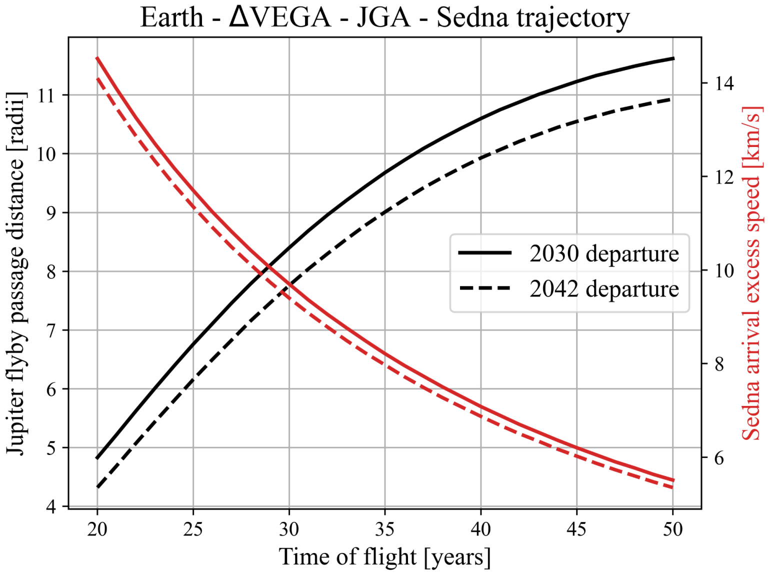

Figure 7 **Earth – ΔVEGA – JGA – Sedna trajectory comparing the arrival excess speed and Jupiter flyby distances for two departure dates against the transit time.**

In the case of the trajectory results presented in Fig. 6 and Fig. 7, the characteristic energy, and a few additional parameters remain nearly constant with transit time. These other important trajectory characteristics are presented in Table 1.

Table 1 Other important parameters for the Earth – ΔVEGA – JGA – Sedna trajectory

	2030 departure	2042 departure
Characteristic energy, C_3 [km^2/s^2]	26	26
Earth passage distance [radii]	8.8	14
Space burn ΔV [km/s]	0.62	0.62

D. Earth–VEGA–JGA–Sedna Trajectory

Another option to increase the transit performance to Sedna is a VEGA maneuver. This adds a Venus and Earth flyby. A VEGA maneuver allows for a lower C_3 value by using some of the gravitational energy of Venus and Earth. By doing this it increases the time of flight but also increases the possible mass on target at Sedna. Fig 8 depicts the flight path and flyby locations of the VEGA maneuver.

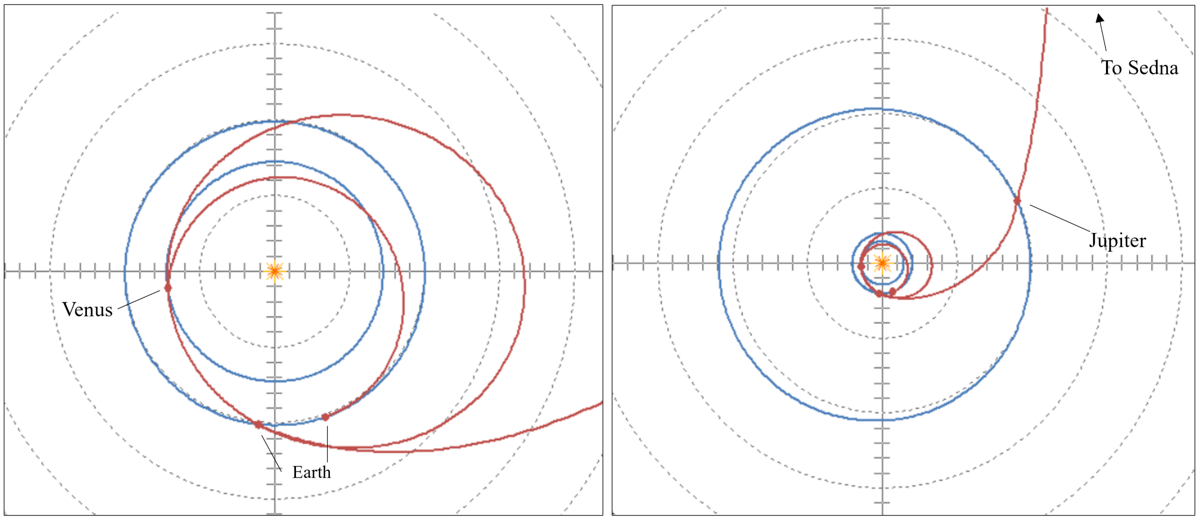

Figure 8 Earth – VEGA – EGA – Sedna trajectory showing (left) the VEGA maneuver, and (right) the JGA and flightpath to Sedna

E. Jupiter flyby radiation dose

A significant factor when comparing the different trajectories is the Jupiter flyby distance. Shorter mission durations typically involve smaller Jupiter flyby distances, resulting in higher radiation doses to the spacecraft. Large exposure to radiation can cause electronic and system failures. The closest flyby distance that is safe and feasible is 2-3 Jovian radii, also taking into account the time spent in the irradiated area. These figures assist with the evaluation of the Jupiter passage distance, allowing specifications for radiation protection to be selected and accounted for, as calculated by [9].

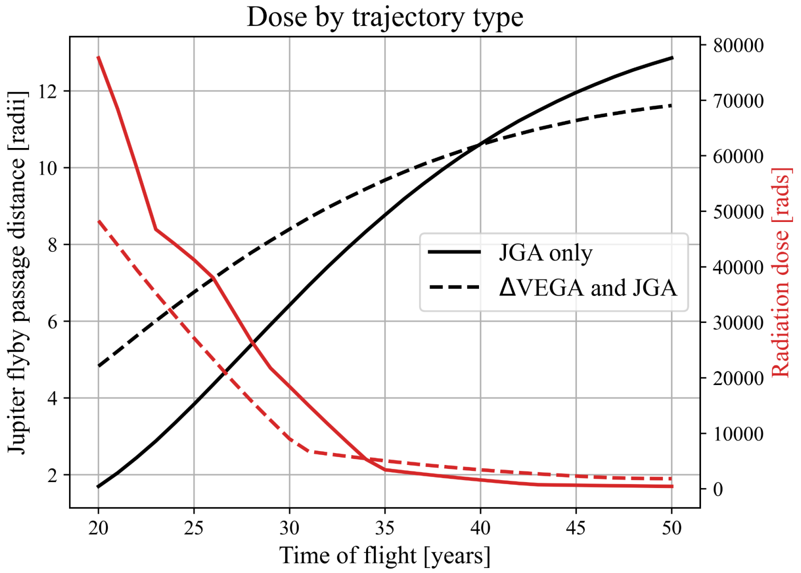

Figure 9 Radiation dose and Jupiter flyby distance against transit time for two different trajectory options.

Figure 8 suggests that ΔVEGA trajectories are favorable when compared to Earth - JGA - Sedna trajectories, in terms of radiation for transit times less than around 35 years. For longer transit times, the radiation dose becomes larger for ΔVEGA trajectories. Indeed, the Jupiter passage distance for trajectories incorporating the ΔVEGA maneuver is less than that for trajectories incorporating only JGAs, for transit times greater than 40 years.

F. Potential lander mass on target (NOTE: mass calculations will be revised)

To approximate the potential mass on target to Sedna for various launch vehicles, we employed NASA's Launch Services Program Performance tools (LSP) by using a constant 30 km^2/s^2 C_3, the upper bound of launches employing a ΔVEGA maneuver. Figure 9 compares launch vehicles by their energy and mass on-target performances.

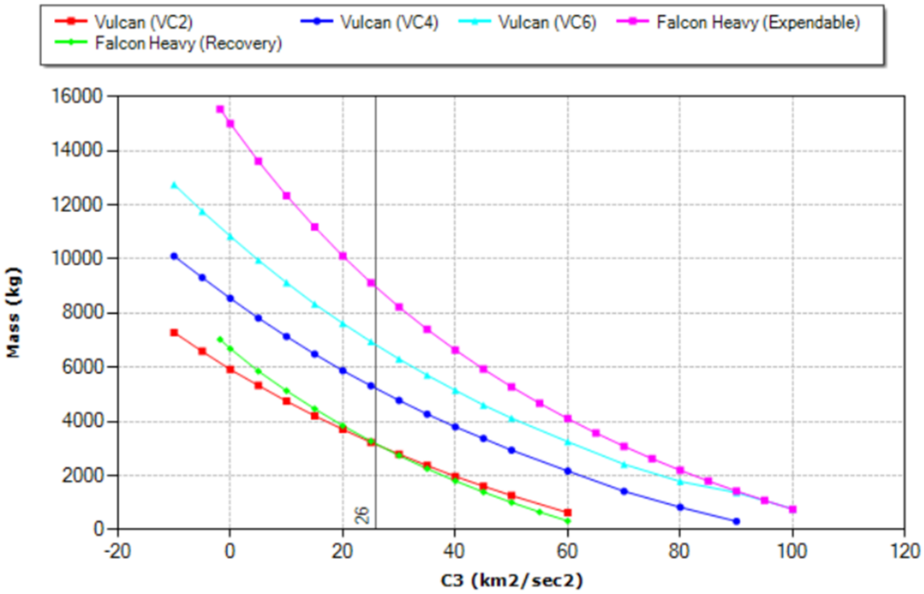

Figure 10 Vulcan VC2-VC6 and Falcon Heavy (recoverable and non-recoverable) outbound mass versus C_3 graphs (from [8])

Table 2 New Glenn, Antares, Vulcan VC2-VC6, & Falcon Heavy (recoverable and non-recoverable) final mass, propellant mass, and target mass

Rocket	C_3 [km^2/s^2]	Earth Outbound Mass [kg]	V_{eq} [km/s]	ΔV [m/s]	Mass (on target) [kg]	Mass (propellant) [kg]
Vulcan VC2	30	2790	3.14	620.9	2289	501
Falcon Heavy (Recover)	30	2740	3.14	620.9	2248	492
Vulcan VC4	30	4780	3.14	620.9	3922	858
Vulcan VC6	30	6310	3.14	620.9	5178	1132
Falcon Heavy (Expendable)	30	8225	3.14	620.9	6749	1476

The data in Table 2 predict the possible mass on target to arrive at Sedna achievable with the characteristic energies and space burn calculations as determined in this study, for Earth - Sedna trajectories employing the ΔVEGA maneuver. Assuming a landing speed of zero km/s, the total delta-V required will be near that of the arrival excess speed but will exceed this number minutely due to Sedna's gravitational pull. Comparing arrival excess speeds against transit time, as shown in Fig. 7 for ΔVEGA trajectories, allows for calculating the potential lander mass on target against transit time, shown in Fig. 10. These values include the gravitational force of Sedna, and are taken at a general radius of orbit around Sedna of 12000 km, and showcase how much mass could be attributed to a lander or any machinery for scientific instruments.

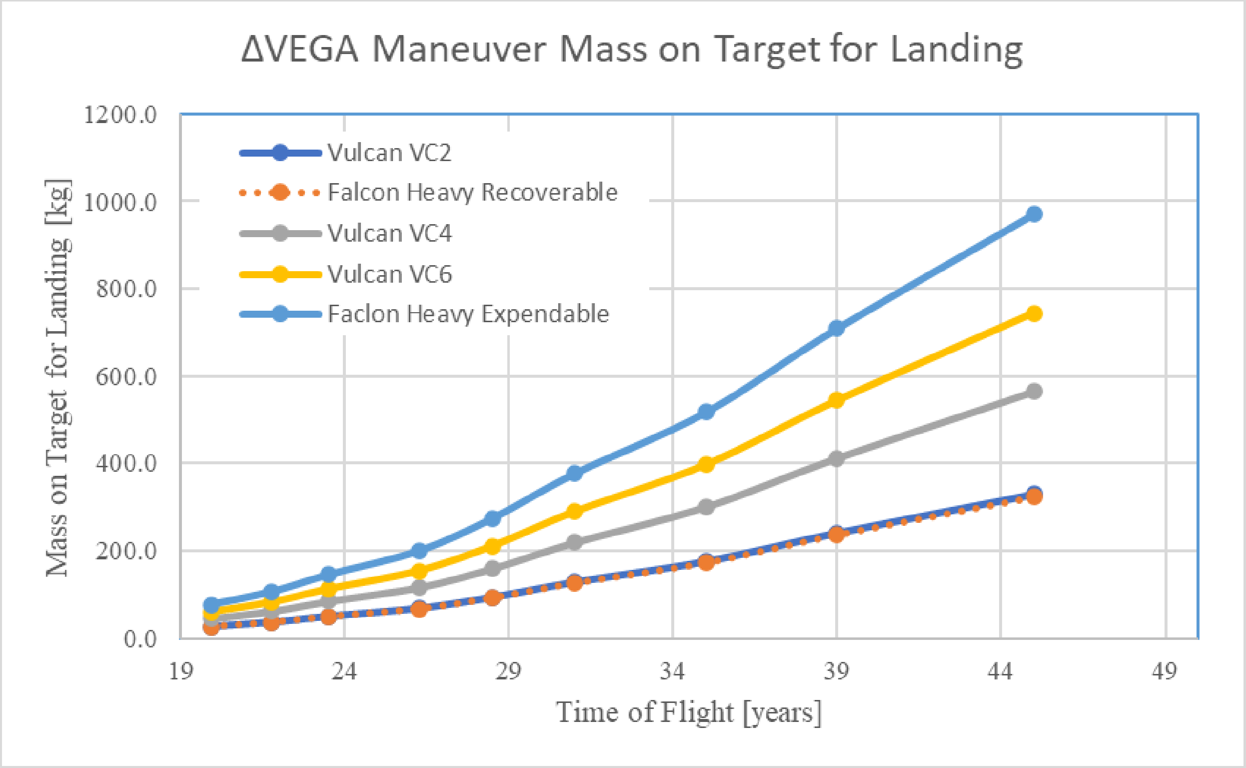

Figure 11 Vulcan VC2-VC6 & Falcon Heavy (recoverable and expendable) expected mass on target versus time of flight, for a specific impulse of 320 seconds for ΔVEGA Maneuver

Figure 10 shows that the mass on target varies from 25 kg at least to about 1000 kg at most, depending on the type of payload desired to land at Sedna. A preferred choice between the six rocket configurations could be chosen and used to reach a minimum threshold of mass on target. The time of flight could also be adjusted to better fit needed mass requirements. The exact values of mass available to land on Sedna are shown in the table below, Table 3. This mass is what can be used for any sort of lander, or mission tool to be used in the mission. This is essentially the dry mass of the rocket for the mission.

Table 3 New Glenn, Antares, Vulcan VC2-VC6, & Falcon Heavy (recoverable and non-recoverable) Mass on target for Landing on Sedna for ΔVEGA Maneuver

Vinf [km/s]	Vulcan VC2 Mass [kg]	Falcon Heavy (Recover) Mass [kg]	Vulcan VC4 Mass [kg]	Vulcan VC6 Mass [kg]	Falcon Heavy (Expend) Mass [kg]
6.0	329.1	323.2	563.9	744.5	970.4
7.0	240.3	236.0	411.7	543.6	708.5
8.0	175.3	172.1	300.3	396.5	516.7
9.0	127.7	125.5	218.9	289.0	376.7
10.0	93.1	91.4	159.5	210.5	274.4
11.0	67.8	66.6	116.1	153.3	199.9
12.0	49.4	48.5	84.6	111.7	145.5
13.0	35.9	35.3	61.6	81.3	105.9
14.0	26.2	25.7	44.8	59.2	77.1

This data can be used to determine which rocket or rocket equivalent could and should be used for each specific purpose, based on the mass and weight of the instruments to be placed on the rocket for the individual mission it should accomplish.

For the VEGA maneuver itself, the mass on target for landing doesn't change a large amount, but it is still considerable when designing a lander and with rocket choice for the mission. The VEGA maneuver has a longer Time of Flight on average but also manages to hold more mass on these same arrival excess speeds. The lower C_3 values of the VEGA maneuver also allow for a higher mass available after leaving Earth's gravity and for more mass on target for landing on Sedna.

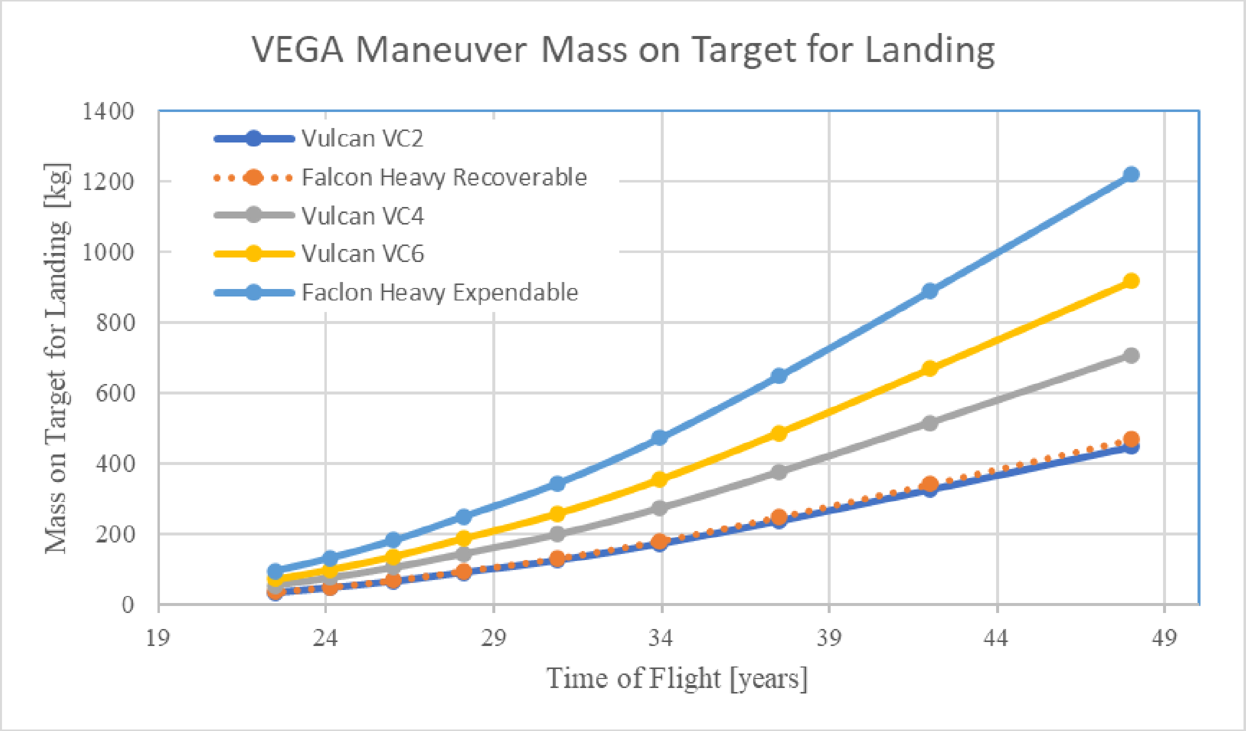

Figure 12 **Vulcan VC2-VC6 & Falcon Heavy (recoverable and expendable) expected mass on target versus time of flight, for a specific impulse of 320 seconds for VEGA Maneuver**

The VEGA maneuver displays a much longer time of flight range compared to the ΔVEGA, with a range from around 22 to 48 years, compared to the prior 20 to 45-year range as the VEGA maneuver generally arrives at faster velocities than the ΔVEGA maneuver. The VEGA maneuver also has more mass on target for landing, as the Falcon Heavy Expendable has about 200 kg more mass at the highest point in measurement. This comparison can be more directly seen in the table below.

Table 4 New Glenn, Antares, Vulcan VC2-VC6, & Falcon Heavy (recoverable and non-recoverable) Mass on target for Landing on Sedna for VEGA Manuver

Vinf [km/s]	Vulcan VC2 Mass [kg]	Falcon Heavy (Recover) Mass [kg]	Vulcan VC4 Mass [kg]	Vulcan VC6 Mass [kg]	Falcon Heavy (Expend) Mass [kg]
6.0	449.7	468.6	708.2	917.2	1219.33
7.0	328.4	342.2	517.1	669.7	890.3
8.0	239.5	249.6	377.2	488.5	649.4
9.0	174.6	181.9	275.0	356.1	473.4
10.0	127.2	132.6	200.3	259.4	344.9
11.0	92.7	96.6	145.9	189.0	251.2
12.0	67.4	70.3	106.3	137.6	183.0
13.0	49.1	51.2	77.4	100.2	133.2
14.0	35.8	37.26	56.3	72.9	97.0

These tables show higher values at comparable arrival excess speeds for mass on target, but fail to show the Time of Flights of these excess speeds. The VEGA maneuver on average takes about 2-3 years extra in its Time of Flight to reach Sedna, and therefore it has more mass available on landing for the same arrival excess speeds as the ΔVEGA maneuver. However, these values do showcase a potential larger mass on target for landing in these VEGA maneuvers.

The comparisons between the VEGA and ΔVEGA maneuvers can be seen when directly compared to one another on the same graph, as seen in Figure 13 as seen below, comparing the Falcon Heavy Expendable mass on targets for the two maneuvers.

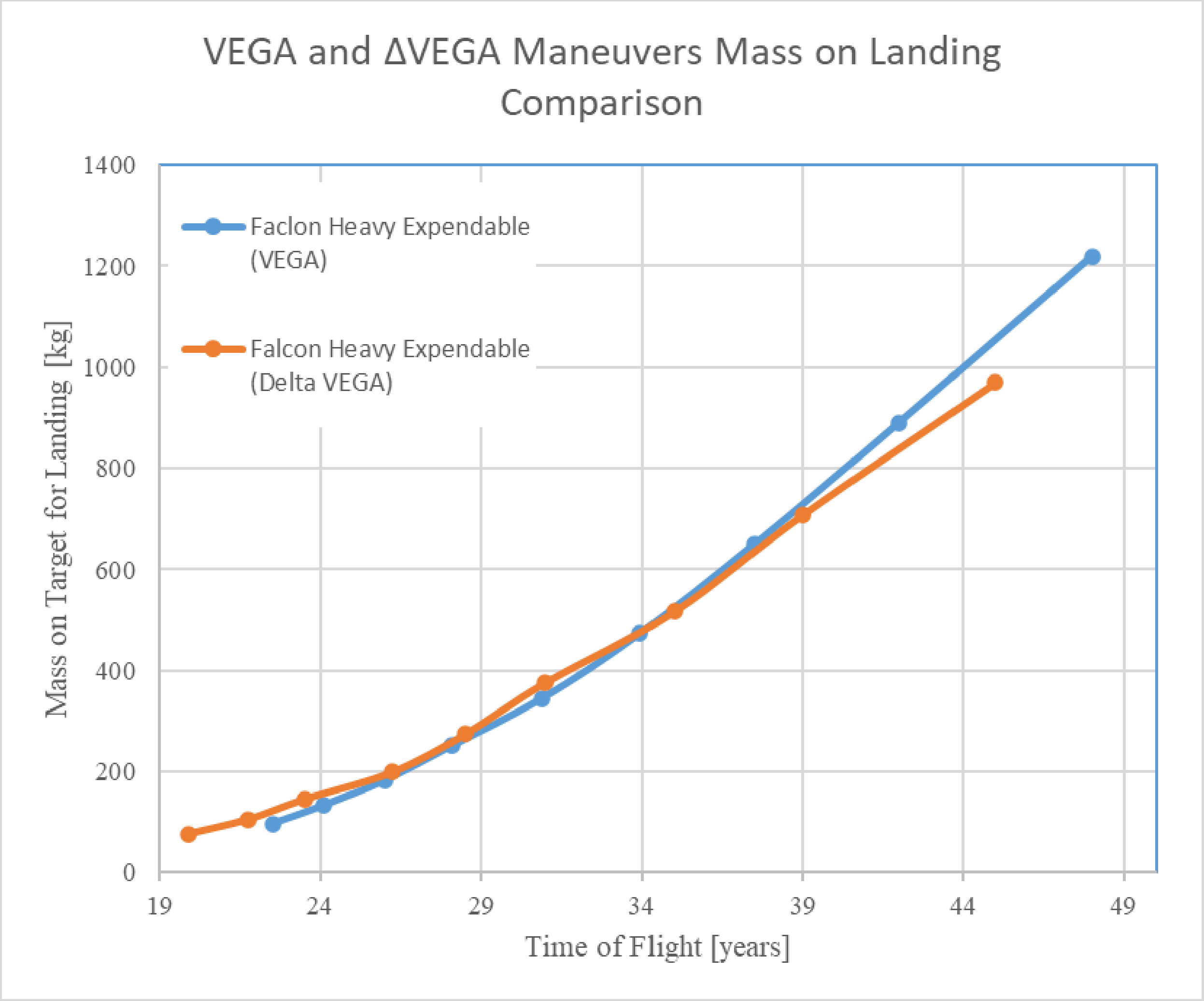

Figure 13 **Falcon Heavy Expendable expected mass on target versus time of flight, for a specific impulse of 320 seconds for VEGA Manuver and ΔVEGA Manuver Comparison**

From this we can see that the VEGA maneuver is a flatter curve than that of the ΔVEGA maneuver, and actually holds more mass on target at larger Time of Flights while losing to the ΔVEGA at lower time of flights. Other than this slight discrepancy, the values are essentially the same in calculations, or very nearly identical especially at average Time of Flgihts around 30-35 years in length. This means that the VEGA maneuver can be freely implemented into the design in order to require less power and overall energy for the actual flight and landing upon Sedna, at no real cost to mass in comparison to the ΔVEGA maneuver.

CONCLUSIONS

In conclusion, the search for trajectories to Sedna has yielded several potential options for an orbiter mission to this distant planet. Through our research and data, we have found several trajectories that could get an orbiter to Sedna as soon as 2070. While the task of reaching Sedna is not without its challenges, including the need for advanced propulsion systems and precise navigation capabilities, the promise of exploring this icy world in hopes that it would unlock the secrets of our universe makes it worth it. The exploration of Sedna represents a significant opportunity to expand our knowledge of the outer solar system and the origins of our planetary neighborhood.

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