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Saturn Escape Options for Cassini Encore Missions

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By escaping the Saturnian system, the Cassini spacecraft can reach other destinations in the solar system while satisfying planetary quarantine. The patched-conic method was used to search for trajectories that depart Saturn via gravity assist at Titan. Trajectories were found that fly by Jupiter to reach Uranus or Neptune, capture at Jupiter or Neptune, escape the solar system, fly by Uranus during its 2049 equinox, or encounter Centaurs. A "grand tour," which visits Jupiter, Uranus, and Neptune, departs Saturn in 2014. Alternatively, Cassini could reach Chiron, the first-discovered Centaur, in 10.5 years after a 2022 Saturn departure.

Nomenclature

a	=	semimajor axis, astronomical unit
d	=	approximate Centaur diameter, km
e	=	eccentricity
i	=	inclination, deg
T_{pen}	=	orbit period on penultimate orbit, before planetary escape, days or years
V_∞	=	hyperbolic excess speed, km/s
$\Delta V_{♃}$	=	velocity-change maneuver applied at Jupiter to target Centaur, m/s
$\Delta V_{\mathrm{retarget}}$	=	velocity-change maneuver applied at Centaur to retarget arrival planet, m/s
$\Delta V_{♄}$	=	velocity-change maneuver applied at Saturn to target Centaur, m/s

Subscripts

♃	=	Jupiter
♄	=	Saturn
♅	=	Uranus
♆	=	Neptune

Introduction

CASSINI [1,2] has had tremendous success in its primary mission since its arrival at Saturn in 2004; it now has the opportunity to surpass the most well-traveled spacecraft to date: Voyager, Pioneer, and Galileo. As Cassini continues to operate beyond its life expectancy, mission designers consider possible extensions to the primary mission. Escape options for Cassini offer great opportunities for further scientific observation beyond the Saturnian system. Satisfying planetary quarantine requirements, however, remains a concern.

There are international guidelines that NASA has adopted to prevent contamination on the surface of another planet or moon that may have (in the past or at present) the potential for harboring life. Yam et al. [3] have assessed a scenario that satisfies the planetary quarantine requirement via impact trajectories at Saturn. Patterson et al. [4] investigate the option of orbits within the Saturnian system that avoid impacting Saturn's moons for 500 years. A third option is to escape the Saturnian system all together.

Cassini can depart Saturn using gravity-assist maneuvers at Titan, Saturn's largest moon. While Cassini is in orbit around Saturn, it can use repeated flybys of Titan to adjust its phase angle, aligning its Saturn-centered orbit with a given hyperbolic escape trajectory. The spacecraft performs one final flyby to get on the escape trajectory and leave Saturn. This satellite-aided escape technique was developed in an early paper by Farquhar and Dunham [5] and applied to Cassini end-of-mission studies by Okutsu et al. [6] and Strange [7].

Saturn escape offers Cassini a wide range of options for extending exploration beyond the primary mission. These options promise a substantial increase in the scientific return from the Cassini mission (over impacting Saturn or remaining in 500-year stable orbits) while preventing the spacecraft from impacting and contaminating any of the moons of Saturn that are protected by planetary quarantine. Some of the options offer scientists a glimpse of celestial bodies and phenomena that have not yet been observed.

Escape Options

We investigate trajectories that 1) impact at Jupiter, Uranus, or Neptune, 2) use a gravity assist at Jupiter to reach Uranus or Neptune, 3) escape the solar system, 4) fly by Uranus during its equinox in 2049, 5) capture into orbit around Jupiter or Neptune, or 6) encounter Centaurs.

We consider trajectories that target Jupiter, Uranus, and Neptune directly and paths that use a Jupiter gravity assist to reach Uranus and Neptune. On each leg, the spacecraft is nominally targeted for an impact with the flyby body or for escaping the solar system (if the V_∞ is large enough). Throughout this paper, we use the term "impact" to always mean collision with the body or with its atmosphere. The flyby option is available if the spacecraft is still operational and able to perform a small trajectory correction maneuver. If the spacecraft is not operational or is not able to perform maneuvers, it will impact the next arrival planet, terminating the mission.

In addition to flybys at the other gas giants, we also study the opportunity for escaping the solar system or capturing into an orbit around Jupiter or Neptune. Escaping the solar system requires a high V_∞, but it has the advantage of keeping the spacecraft "alive." Capturing at Jupiter or Neptune, however, requires low V_∞ and provides more science than flybys, but at the cost of (probably minimal) mission operations. We investigate the Saturn departure windows and the outgoing V_∞ at Saturn that are required to escape the solar system or capture at Jupiter or Neptune.

There is also scientific interest in observing Uranus during its next equinox, when the plane of the rings passes through the sun, in 2049 [8]. Uranus is tilted at a 98-deg angle, so that during a solstice nearly the entire northern (or southern) hemisphere is in total darkness.

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During equinox, when the sun spends equal time shining on both sides of Uranus's equator, the atmosphere of Uranus will warm up and scientists expect there will be fascinating changes to observe. Because of its 84-year orbital period, equinox only occurs on Uranus once every 42 years. For this reason, we investigate the Saturn departure window for arrival at the upcoming Uranus equinox in 2049.

The last and perhaps the most unexplored option is an encounter with a Centaur, a small solar system body with a semimajor axis between the orbits of Jupiter and Neptune (i.e., 5.5 AU$<$ $a < 30.1$ AU). Because of their extreme orbit characteristics, Centaurs have avoided the disruptive gravity fields of the gas giants. Centaur orbits differ significantly from those of the major planets, which are nearly circular and lie in the ecliptic plane; their orbits can be extremely eccentric and highly inclined. There is significant scientific interest in Centaurs because these objects may contain primordial materials that hold valuable clues about the formation of our solar system.

Gravity-Assist Escape Problem

The idea of using a satellite's gravity to reduce the capture ΔV has been studied since 1968 [9–13]. Upon arrival at a planet (e.g., Jupiter), the energy of the spacecraft relative to the planet can be reduced using gravity assist from a natural satellite (e.g., Ganymede). A capture at the planet can then be achieved with a smaller propellant cost, or even ballistically if the arrival V_∞ is small enough.

The reverse of the gravity-assist capture (or satellite-aided capture) problem is called gravity-assist escape (or satellite-aided escape), in which we use gravity assists from a moon to increase the energy of the spacecraft to escape the planet. An example of gravity-assist escape is the use of lunar swing-by to escape Earth's gravity [5,14].

Figure 1 provides a schematic of the gravity-assist escape problem. We assume a spacecraft, orbiting about planet 1 (e.g., Saturn), is about to encounter a gravity-assist (GA) body (a satellite of planet 1, for example, Titan). The GA body boosts the spacecraft's energy enough to escape planet 1 without any propulsive ΔV (other than negligible targeting maneuvers).

Figure 2 shows a vector diagram of the GA body flyby. The planet 1 escape-velocity sphere has a radius equal to $V_{sc} = \sqrt{2\mu/r}$, which comes from a variation of the energy equation $V_{sc} = \sqrt{V^2_{\infty/\mathrm{planet1}} + 2\mu/r}$ with zero hyperbolic excess velocity $V_{\infty/\mathrm{planet1}} = 0$ (a parabolic orbit with respect to planet 1). The $V_{\infty/\mathrm{ga}}$ sphere is centered at the tip of the GA body velocity vector $\mathbf{V}_{\mathrm{ga}}$, and has a radius equal to the $\mathbf{V}_{\infty/\mathrm{ga}}$ magnitude. We note that a part of this $V_{\infty/\mathrm{ga}}$ sphere is enclosed by the escape-velocity sphere. We also note that the tip of the $\mathbf{V}_{\mathrm{sc/planet1,out}}$ vector must be located on the surface of the $V_{\infty/\mathrm{ga}}$ sphere. If the tip of the $\mathbf{V}_{\mathrm{sc/planet1,out}}$ vector rests somewhere on the portion of the $V_{\infty/\mathrm{ga}}$ sphere that is not enclosed by the planet 1 escape-velocity sphere (the shaded region on the $V_{\infty/\mathrm{ga}}$ sphere), then the spacecraft will escape planet 1. A spacecraft whose velocity vector tip is inside the escape-velocity sphere will remain in an elliptical orbit around planet 1.

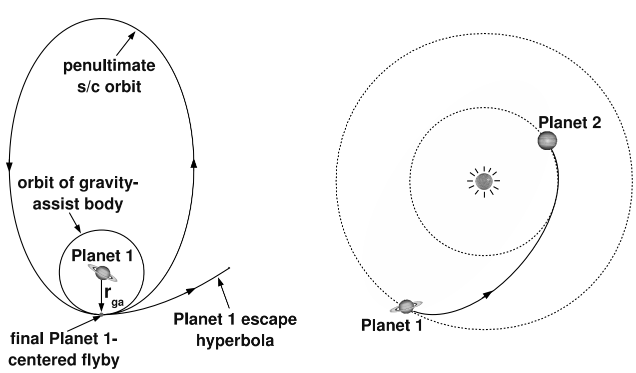

Fig. 1 Schematic of the gravity-assist escape problem.

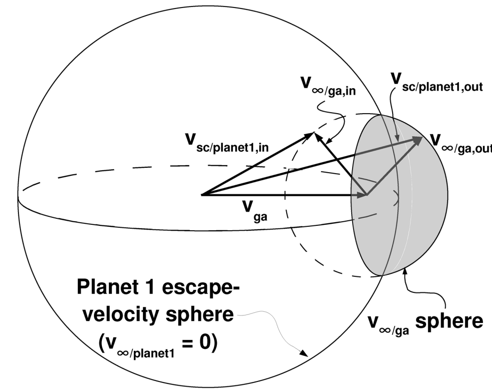

Fig. 2 Flyby vector diagram of a gravity assist from a satellite.

For a given incoming $\mathbf{V}_\infty$ vector at the GA body $\mathbf{V}_{\infty/\mathrm{ga,in}}$, there exists a family of outgoing orbits (obtained by varying the flyby conditions), each with its own outgoing $\mathbf{V}_\infty$ vector with respect to the GA body $\mathbf{V}_{\infty/\mathrm{ga,out}}$. If the flyby of the GA body provides enough gravity-assist ΔV to swing the $\mathbf{V}_{\infty/\mathrm{ga,out}}$ vector outside the planet 1 escape-velocity sphere and onto the shaded region of the $V_{\infty/\mathrm{ga}}$ sphere, then the spacecraft will escape planet 1 with hyperbolic excess velocity $\mathbf{V}_{\infty/\mathrm{planet1}}$. Each $\mathbf{V}_{\infty/\mathrm{ga,out}}$ corresponds to a unique $\mathbf{V}_{\infty/\mathrm{planet1}}$ for that particular situation. We must determine the $\mathbf{V}_{\infty/\mathrm{planet1}}$ such that the spacecraft will arrive at the desired location, planet 2 (for example, Jupiter). For the heliocentric transfer from planet 1 to planet 2, the Lambert problem can be solved to find a set of $\mathbf{V}_{\infty/\mathrm{planet1}}$ with various times of flight (TOF) [15–17].

For the Cassini end-of-mission and encore scenario, we turn our attention to the very last flyby at Titan. Before the final Titan encounter (on the penultimate orbit), we assume the spacecraft orbits about Saturn with a period of T_{pen}. Figure 3 plots the maximum escape speed relative to Saturn $V_{\infty/\text{♄}}$ for a set of penultimate orbits with various periods (equations for obtaining the curves in Fig. 3 are derived in Strange [7]). We consider 5.50 km/s as a representative value for $V_{\infty/\mathrm{Titan}}$ for Cassini end-of-mission scenarios. With this value of $V_{\infty/\mathrm{Titan}}$, a spacecraft in a one-year orbit (with a flyby altitude of 900 km) can escape Saturn with a V_∞ as high as 2.4 km/s. To achieve a higher escape V_∞, we note from Fig. 3 that a lower $V_{\infty/\mathrm{Titan}}$ or a longer period before escape are required. Lowering the flyby altitude at Titan would also increase the Saturn escape V_∞, but because Titan has a substantial atmosphere, we restrict the minimum flyby altitude for our analysis to be no lower than 900 km (the actual minimum flyby altitude adopted for the Cassini mission is 950 km [1,2]).

The $V_{\infty/\mathrm{Titan}}$ can be changed using V_∞ leveraging [18] (by applying a ΔV at apoapsis) and by taking advantage of solar

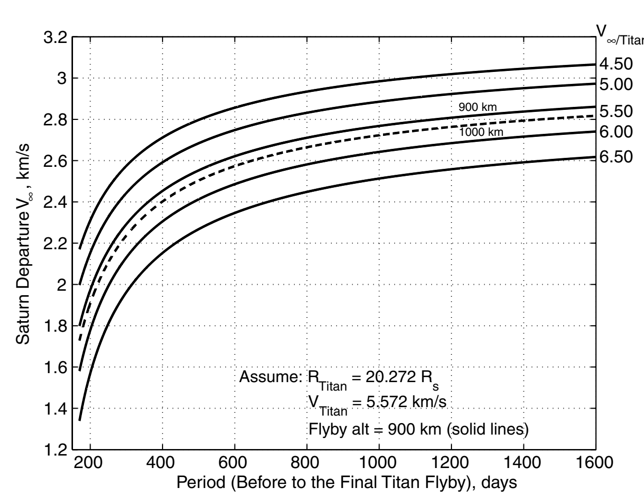

Fig. 3 Saturn escape V_∞ vs final orbit period about Saturn.

perturbations on large orbits (depending on the orientation of the orbit relative to the sun, solar perturbations can increase or decrease the V_∞ relative to Titan) [19]. For example, a ΔV of about 20 m/s plus solar perturbations can decrease the $V_{\infty/\mathrm{Titan}}$ by 1 km/s on a 446-day orbit [19]. A smaller V_∞ relative to Titan allows more bending on the final Titan flyby and thus a higher Saturn departure V_∞ can be achieved.

Up to this point, we have assumed that the penultimate spacecraft orbit is conveniently oriented so that the final Titan flyby will point the $\mathbf{V}_{\infty/\mathrm{planet1}}$ in the desired direction to reach the destination. We note that the $\mathbf{V}_{\infty/\mathrm{planet1}}$ is a three-dimensional vector, which has its largest component in Saturn's equatorial plane but may also have a significant out-of-plane component (typically inclined by 30 deg, due in part to the 26-deg tilt of Saturn's axis with respect to the ecliptic). To ensure that the correct orientation is obtained, a series of successive nonresonant Titan-to-Titan transfers can be implemented to align the line of apsides. In addition, a series of crank-up maneuvers can increase the spacecraft orbital inclination to match the out-of-plane component of the $\mathbf{V}_{\infty/\mathrm{planet1}}$. A method of matching the spacecraft $\mathbf{V}_\infty$ vector with the $\mathbf{V}_\infty$ vector computed from the interplanetary Lambert solution is described by Okutsu et al. [6], in which orbit period pump-ups and pump-downs and inclination crank-ups and crank-downs are used during flybys of Titan. Diehl et al. [20] discuss this technique in connection with the Galileo mission.

Okutsu et al. [6] present a numerically integrated trajectory that escapes Saturn to impact Jupiter, obtained using this V_∞-matching technique. It is assumed that the V_∞-matching technique described by Okutsu et al. can be used to leave the Saturnian system without propulsive ΔV on a trajectory to a destination of our choosing. For our escape options, we employ patched-conic techniques and draw planetary states from an analytic ephemeris. As a proviso, we note that our results are preliminary designs that require higher fidelity modeling to confirm their suitability for the Cassini mission.

Design Techniques for Centaur Encounter Trajectories

Nontargeted and Targeted Centaur Encounter Trajectories

The method we use in searching for trajectories that encounter Centaurs is one of brute force. We use the term "nontargeted Centaur encounter" to indicate a flyby of a Centaur that occurs accidentally while en route to another planet. If the nontargeted encounter distance is too great, we can reduce the flyby altitude to an arbitrarily small value via a ΔV maneuver; we refer to this case as a "targeted Centaur encounter," (our nomenclature is derived from Diehl et al. [20]). We search for encounters with all 211 Centaurs that are known at the time of this writing.

The first step in searching for nontargeted Centaur encounters is to find a series of Lambert solutions from Saturn to Jupiter, Uranus, or Neptune, within a departure window (e.g., from 2010 to about 2025) for the Cassini spacecraft. Then each Lambert trajectory is divided into 100 discrete segments (where the segment size typically ranges from a few weeks to a few months). Trajectories that encounter multiple planets are analyzed one leg at a time. We obtained orbital elements of the Centaurs from the Minor Planet Center[§] of the International Astronomical Union. Centaurs with orbits that offer no possibility for encounter on the given trajectory leg are filtered out: Centaurs with perihelia larger than the aphelia of both Saturn and the arrival planet or aphelia smaller than the perihelia of both Saturn and the arrival planet are not considered for trajectories to that particular arrival planet. All the remaining Centaurs are propagated forward to each of the 100 points in time corresponding to the positions of the spacecraft (on each planet-to-planet leg). The distances between the spacecraft and all the qualified Centaurs are calculated at each point along every trajectory. Encounters with miss distances larger than 100×10^6 km or times of flight to the Centaur greater than 30 years (except for Saturn–Jupiter–Neptune tours where the limit is 50 years) are filtered out. The closest nontargeted approach of a Centaur that we found within this mission window was at a distance of about 1.5×10^6 km, and so we discovered no "accidental" nontargeted encounters that appeared to offer high-quality science flybys.

The next step is to turn these nontargeted encounters (typically with miss distances of about 10–20 million km) into targeted encounters by inserting a small ΔV maneuver (at Saturn, shortly after the final Titan flyby) to shrink the miss distance down to zero kilometers. The outgoing $\mathbf{V}_\infty$ vector at Saturn is determined for a new Lambert arc that arrives at the Centaur at the time of the minimum miss distance on that trajectory. The maneuver required to impact the Centaur $\Delta V_{♄}$ is the difference between the new $\mathbf{V}_\infty$ vector and the $\mathbf{V}_\infty$ vector from the original Lambert solution. The encounter date is then allowed to vary, using a simple single-variable unconstrained optimization technique to minimize the magnitude of the $\Delta V_{♄}$ maneuver. This optimization process also alleviates the limitations on search resolution due to the large step size (several months) between discrete trajectory segments. We note that these $\Delta V_{♄}$ maneuvers may be eliminated in the tour design leading up to the final Titan flyby as demonstrated in Okutsu et al. [6].

After performing a $\Delta V_{♄}$ maneuver to target a Centaur, the spacecraft is no longer on the original interplanetary trajectory that terminates at the arrival planet. To ensure that Cassini does not return to Saturn (which could violate the planetary quarantine requirements concerning Titan), we target the spacecraft to impact Jupiter, Uranus, or Neptune. Using the same process, a second ΔV maneuver (to be performed at or near the Centaur encounter) is calculated to retarget the arrival planet on the original interplanetary tour. The arrival date is again allowed to vary to minimize the retargeting ΔV maneuver $\Delta V_{\mathrm{retarget}}$. These results are intended for preliminary identification of promising trajectories for which the $\Delta V_{\mathrm{retarget}}$ can be further reduced by an optimization algorithm proposed by Byrnes and Bright [21]. Several attractive trajectories were found and are shown in the results section.

Direct Centaur Encounter Trajectories

We use the term "direct Centaur encounter" for trajectories for which the primary and only destination is a Centaur. For these direct missions, there is no option for an arrival at a major planet following the Centaur flyby; the spacecraft would return to intersect the orbit of Saturn. In our search for these trajectories, we generated families of Lambert solutions that satisfy certain constraints (e.g., departure date between 2010 and 2030 and times of flight up to 25 years). We plotted V_∞ contours as a function of Saturn departure date and TOF (known as "porkchop plots") to represent the solution space for each Centaur. Porkchop plots were created for all 211 known Centaurs, the most recently discovered being 2007 RH_{283}. We selected a few Centaurs that offered trajectories with both low Saturn departure V_∞ and short times of flight.

Results

Impact at Jupiter, Uranus, or Neptune

Figures 4–6 are porkchop plots that show direct trajectories that impact Jupiter, Uranus, and Neptune (i.e., without any intermediate flybys). There are several trajectories here that offer Saturn departure V_∞ below Cassini's nominal achievable departure V_∞ of 2.4 km/s. Because there are methods for increasing the Saturn departure V_∞ (such as using a larger penultimate orbit, V_∞ leveraging, etc.), we do include in our searches (so as to not miss important potential options) trajectories that require Saturn departure V_∞ somewhat greater than 2.4 km/s.

Gravity Assist at Jupiter to Reach Uranus or Neptune

Gravity assist at Jupiter, because of the planet's great mass, has been the most fruitful nonpowered maneuver that mission designers have at their disposal. Seldom are missions to the outer planets considered without help from Jupiter. One of the most promising trajectories that we found was a grand tour that uses a gravity assist at Jupiter to visit both Uranus and Neptune, as shown in Fig. 7.

[§]Data available at Minor Planet Center database, http://www.cfa.harvard.edu/iau/lists/Centaurs.html.

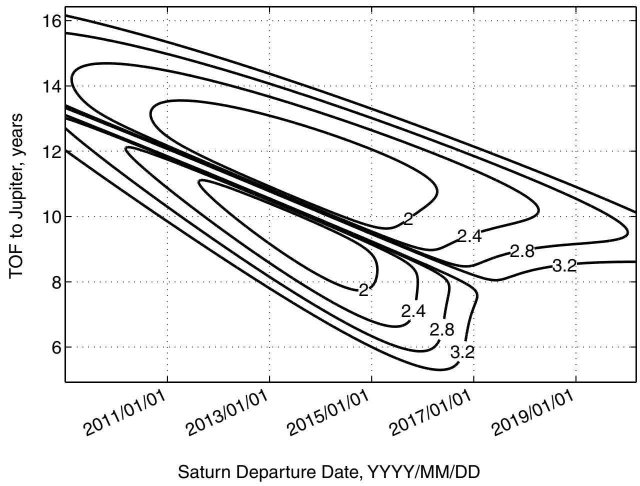

Fig. 4 Porkchop plot showing trajectories that impact at Jupiter; contours are Saturn departure V_∞ in kilometers per second.

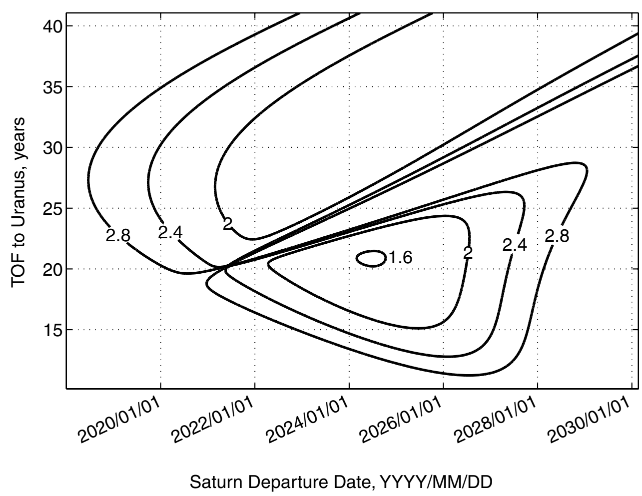

Fig. 5 Porkchop plot showing trajectories that impact at Uranus; contours are Saturn departure V_∞ in kilometers per second.

The details of the grand tour shown in Fig. 7 are presented in Table 1. The grand tour presented in Fig. 7 is the shortest of a family of similar tours for which the TOF range from 47 to 87 years. Cassini could depart Saturn on one of these grand tour trajectories any time between June 2012 and January 2015. These grand tours encounter

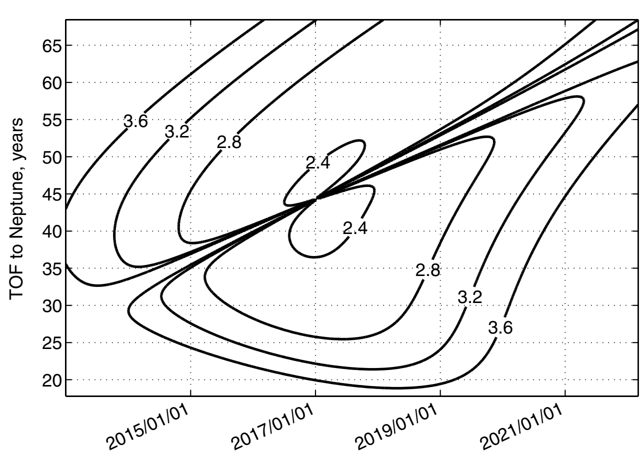

Fig. 6 Porkchop plot showing trajectories that impact at Neptune; contours are Saturn departure V_∞ in kilometers per second.

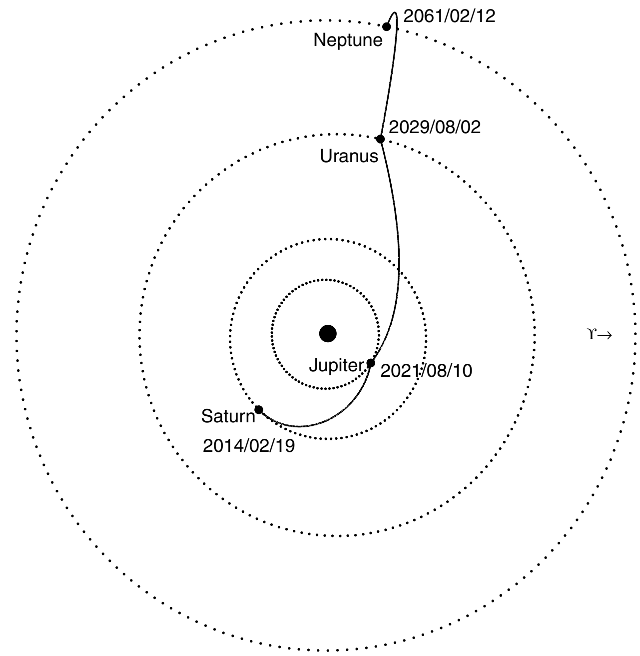

Fig. 7 Cassini grand tour trajectory that visits Jupiter, Uranus, and Neptune.

Jupiter, Uranus, and Neptune, targeting for impact at each of these encounter bodies (to end the mission in case Cassini becomes inoperable). If, however, Cassini is able to perform trajectory correction maneuvers, then the flyby distance can be raised above the surface of the planet and Cassini can continue on to the next planet in the tour.

Solar System Escape

The scenario of escaping the solar system provides an alternative to impacting a gas giant to terminate the mission. Sending the spacecraft out of the solar system ensures the adherence to planetary quarantine requirements, while at the same time keeping the spacecraft alive for continuation of the mission.

Table 2 shows the minimum V_∞ required to escape the solar system at various planets. To escape the solar system directly from Saturn, a departure V_∞ of at least 4.0 km/s with respect to Saturn is required. A V_∞ this large is not achievable with Titan gravity assists alone. However, we may be able to leave the Saturnian system and use a gravity assist from another gas giant to escape the solar system.

We consider the scenario of a Saturn–Jupiter sequence. From Table 2, we note that an arrival V_∞ of at least 5.23 km/s is necessary for achieving solar system escape. But satisfying the minimum orbital energy requirement is not sufficient to escape the solar system; the flyby body must also be capable of bending the trajectory from an eccentric to a hyperbolic orbit with a minimum flyby altitude that is feasible. Jupiter's great mass affords significant bending capability at reasonable flyby distances. The trajectories in the shaded region in Fig. 8 can escape the solar system. In every case, these unconstrained flyby distances are greater than 43 Jupiter radii (well outside the 26.3 R_J orbital radius of Callisto). Figure 8 shows that the minimum Saturn departure V_∞ required for Cassini to escape the solar system after a Jupiter flyby is about 2.2 km/s. The time of flight to Jupiter can be as low as 7 years (assuming Cassini can depart Saturn with a maximum of 2.4 km/s V_∞).

We also consider a Saturn–Uranus sequence in Fig. 9. We see that Cassini can escape the solar system after a Uranus flyby with a Saturn departure V_∞ as low as 1.8 km/s or a time of flight as low as 13 years. The trajectories in Fig. 9 that escape the solar system (shown in the shaded region) can do so with Uranus flyby distances greater than 2×10^6 km.

Another option considered here is to fly Cassini into the sun to dispose of the spacecraft while expanding its scientific return.

Table 1 Cassini grand tour trajectory

Body	Encounter date	V_∞, km/s	Flyby distance, km	TOF since last event, yrs
Saturn	19 Feb 2014	2.40 [a]	——	——
Jupiter	10 Aug 2021	5.67	781,598	7.5
Uranus	02 Aug 2029	8.91	157,380	8.0
Neptune	12 Feb 2061	5.46	——	31.5

[a]Cassini can depart Saturn with a V_∞ as high as 2.4 km/s assuming $T_{\text{pen}} = 365$ days and the final Titan flyby altitude is 900 km.

Table 2 Minimum V_∞ required to escape the solar system

Planet	V_∞, km/s
Jupiter	5.23
Saturn	4.00
Uranus	2.73
Neptune	2.24

However, lowering Cassini's perihelion to below 1 solar radius (both turning Cassini into a solar probe and decisively ending the mission) is not feasible. Trajectories on which Cassini performs a gravity assist at Jupiter to turn toward the sun require a Saturn departure V_∞ of at least 5.5 km/s; gravity assists from Uranus or Neptune would require departing Saturn with at least 3.8 km/s or 3.6 km/s V_∞, respectively. Saturn escape via Titan gravity assist can offer Cassini a nominal departure V_∞ of about 2.4 km/s; even with the techniques for increasing Saturn departure V_∞ that we discuss here, achieving values as high as 3.6 km/s is not feasible.

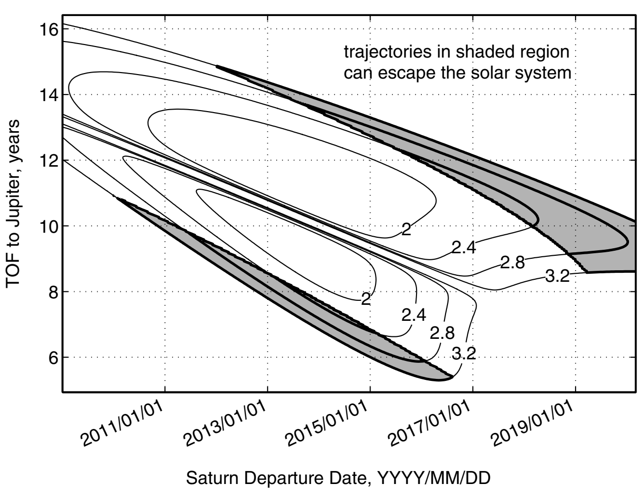

Fig. 8 Saturn–Jupiter trajectories that can escape the solar system; contours are Saturn departure V_∞ in kilometers per second.

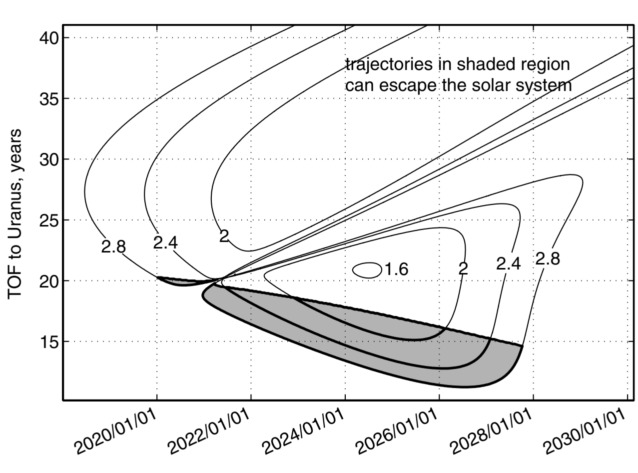

Fig. 9 Saturn–Uranus trajectories that can escape the solar system; contours are Saturn departure V_∞ in kilometers per second.

Uranus Flyby During Its Equinox in 2049

Observations of Jupiter, Saturn, and Pluto during their equinoxes provided scientists with valuable information about the planets and their moons. A flyby of Uranus during this orbital event may enable scientists to explore newly discovered faint rings, examine a rapidly changing atmosphere, and map brightness variations on the larger moons [8]. We provide in Fig. 10 an example of a trajectory that encounters Uranus during its next equinox in 2049. This particular trajectory has a Saturn departure V_∞ of 1.7 km/s, a low value that gives plenty of room for variation in flyby altitude.

Capture at the Gas Giants

Capturing the Cassini spacecraft via a propulsive maneuver is not possible with the limited amount of propellant that remains onboard the spacecraft. It may be possible though to capture the spacecraft ballistically using satellite-aided capture. This technique is very similar to the satellite-aided escape method described earlier, but in reverse order. Rather than using the moon's gravity to boost the energy of the spacecraft, we target a leading-edge flyby of the selected moon to reduce the spacecraft's energy. If we can slow the spacecraft down sufficiently, we can get a ballistic capture at the planet. Potential options for capturing at Jupiter, Uranus, or Neptune using this technique are considered here.

As with the gravity-assist escape problem, the phasing of the moons remains an important concern: the moon must be in the right place at the right time with respect to the incoming spacecraft trajectory. In Figs. 11 and 12, we show the capability of selected moons of Jupiter and Neptune to capture spacecraft into orbit at their respective planets from an energy perspective alone (i.e., phasing is not taken into account). Another concern for these satellite-aided

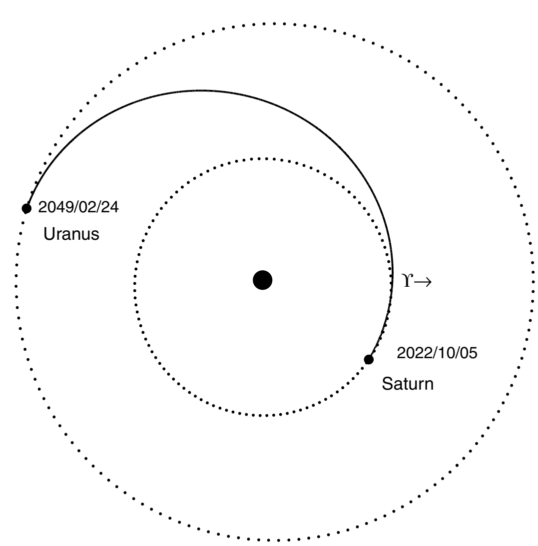

Fig. 10 Trajectory that flies by Uranus during its equinox in 2049.

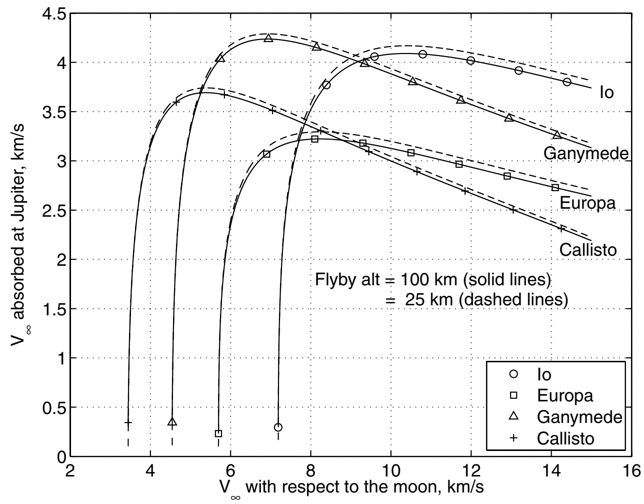

Fig. 11 Envelope for satellite-aided capture at Jupiter.

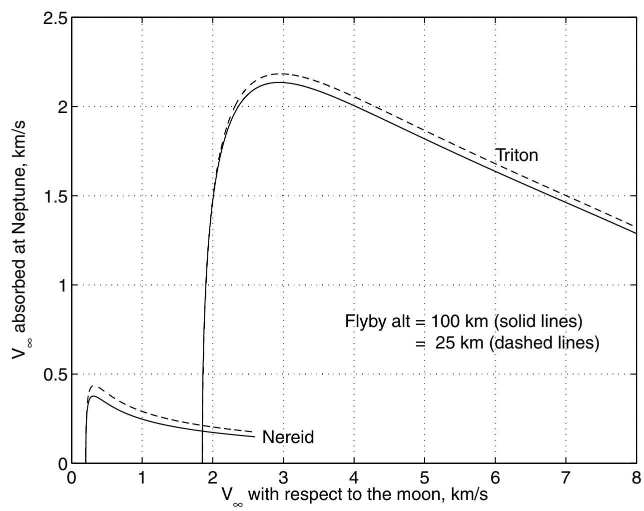

Fig. 12 Envelope for satellite-aided capture at Neptune.

capture trajectories is that we not only need low Saturn departure V_∞, we also need low arrival V_∞. Several trajectories with both low departure and arrival V_∞ are shown in Table 3. These trajectories are representative of families of similar trajectories. The satellites of Uranus are not capable of absorbing enough arrival V_∞ (even neglecting the problematic 98-deg tilt of Uranus's axis, which would restrict times of arrival to the solstices).

We note that, for these trajectories, with such low arrival V_∞, all four of Jupiter's largest moons are capable of absorbing enough of the spacecraft's energy to capture it into the Jovian system. Also, the magnitude of the V_∞ is so much lower than the maximum absorbable V_∞ (indicated by the lines on Fig. 11) that an optimal satellite configuration is not necessary. This margin reduces the phasing problem at Jupiter significantly. The minimum flyby altitude constraints in Figs. 11 and 12 are 100 km (indicated by solid lines) and 25 km (indicated by dashed lines).

Figure 12 shows the maximum absorbable Neptune arrival V_∞ available from Neptune's two largest moons, Triton and Nereid. We note that Nereid's orbit is highly eccentric ($e \approx 0.75$); the curves for Nereid in Fig. 12 are drawn assuming an encounter with Nereid where its velocity is greatest, at periapsis.

The arrival V_∞ in Table 3 make it immediately clear that ballistic capture is only possible at Triton, Neptune's largest moon. At Neptune, with only one moon capable of capturing the spacecraft, the phasing issue leads to fewer capture options compared to arrival at Jupiter.

There are a few important things to note about Triton's orbit when considering it for satellite-aided capture: 1) Triton's orbital period is short (about 5.9 days), which affords a high frequency of opportunities for encountering Triton in an optimal configuration, however, 2) Triton's orbit is highly inclined with respect to the ecliptic plane (the plane Cassini will most likely be traveling in), which decreases the effectiveness of a Triton flyby (or constrains it to occur at or near a solstice) and, lastly, 3) Triton's orbit is retrograde, opposite the direction of Neptune's rotation which will require an abnormal (though not necessarily more difficult) approach strategy.

Centaur Encounters

Targeted Centaur Encounter Trajectories

When high-altitude nontargeted Centaur encounters appear while en route to one of the outer planets, a slight perturbation from the nominal interplanetary trajectory can greatly reduce the encounter distance and provide a low-altitude flyby of the Centaur. Such a perturbation may require only a small ΔV maneuver, shown in Tables 4–7. Trajectories presented in Tables 4–7 are representative of families of nearby trajectories with slightly different V_∞ and departure dates. In our search for targeted trajectories, these are the only families that we identified that have reasonably low TOF and ΔV (i.e., TOF less than about 30 years and ΔV less than about 200 m/s). As mentioned before, the $\Delta V_{♄}$ or $\Delta V_{♃}$ maneuvers can most likely be eliminated in the tour at Saturn or in the flyby at Jupiter, respectively. During the course of the actual mission, optical navigation techniques can enable an arbitrarily close flyby of the Centaur.

Actually impacting a Centaur to end the mission, however, is not desirable, because if the spacecraft is still functioning, the science return of the encounter would be of high value. After the Centaur flyby, a $\Delta V_{\text{retarget}}$ maneuver would be performed to retarget the spacecraft for impact at the arrival planet (that was the destination on the original interplanetary trajectory) to terminate the mission. Because of the small mass of these Centaurs, a gravity assist from the Centaur cannot provide this $\Delta V_{\text{retarget}}$. If the retargeting maneuver is not performed on one of these targeted Centaur encounter trajectories, Cassini could return to the orbit of Saturn and could possibly violate the planetary quarantine requirements by impacting at Titan.

Several trajectories are shown that have departure V_∞ that are larger than the nominal departure V_∞, which is 2.4 km/s. It is possible to increase the departure V_∞ with respect to Saturn by increasing the period of the penultimate orbit T_{pen} and orienting the line of apsides of the spacecraft orbit so that solar perturbations work in our favor. With the proper spacecraft orbit configuration and a large enough orbit period, solar perturbations will raise the periapse radius, decrease eccentricity, and decrease V_∞ with respect to Titan. A lower V_∞ at Titan allows more bending from a gravity assist at Titan, which can increase the V_∞ with respect to Saturn.

Direct Centaur Encounter Trajectories

Although the targeted Centaur encounter trajectories hold the possibility of delivering the spacecraft to another planet and safely ending the mission, the flight times are long and the Saturn departure

Table 3 Possible satellite-aided capture trajectories at Jupiter and Neptune

Depart date	Saturn departure V_∞, km/s	Arrival body	Arrival V_∞, km/s	TOF, yrs
05 Aug. 2011	1.80	Jupiter	1.90	12.38
06 May 2014	1.80	Jupiter	2.27	9.22
13 Sept. 2016	2.40	Neptune	1.61	46.45
31 Oct. 2016	2.40	Neptune	1.61	43.12

Table 4 Targeted Centaur encounters on the way to Uranus, ♄ → ♅

Depart date	Saturn V_∞, km/s	Centaur	TOF, yrs	$\Delta V_{♄}$, m/s	$\Delta V_{\mathrm{retarget}}$, m/s
29 Oct. 2025	1.70	2003 QC_{112}	22.06	12.8	123.1
10 Aug. 2027	2.80	2003 QC_{112}	23.08	9.5	104.0

Table 5 Targeted Centaur encounters on the way to Neptune, ♄ → Ψ

Depart date	Saturn V_∞, km/s	Centaur	TOF, yrs	$\Delta V_{♄}$, m/s	$\Delta V_{\mathrm{retarget}}$, m/s
19 April 2019	2.80	Chiron	11.86	154.4	68.7
11 Feb. 2020	2.60	2003 LH_7	17.36	37.5	11.6
18 Feb. 2020	2.60	2003 LH_7	17.33	45.0	6.7

Table 6 Targeted Centaur encounters en route to Uranus, on an SJU [a] tour, ♄ → ♃ → ♅

Depart date	Saturn V_∞, km/s	Centaur	TOF, yrs	$\Delta V_{♃}$, m/s	$\Delta V_{\mathrm{retarget}}$, m/s
02 June 2021	2.70	1999 OX_3	8.76	9.2	122.2
17 July 2021	2.50	1999 OX_3	8.65	8.4	151.7
12 July 2023	2.40	1994 TA	12.20	36.9	63.4
15 July 2023	2.40	1994 TA	12.13	50.6	5.1
22 March 2021	2.80	2003 QP_{112}	11.77	26.2	0.5
21 March 2021	2.80	2003 QP_{112}	11.78	2.7	2.9
23 July 2028	2.80	2005 CC_{79}	9.43	41.2	22.4
18 March 2021	2.80	2007 RH_{283}	17.28	2.9	30.7

[a]Saturn–Jupiter–Uranus.

Table 7 Targeted Centaur encounters en route to Neptune, on an SJN [a], tour ♄ → ♃ → Ψ

Depart Date	Saturn V_∞, km/s	Centaur	TOF, years	$\Delta V_{♃}$, m/s	$\Delta V_{\mathrm{retarget}}$, m/s
20 March 2021	2.80	2002 PQ_{152}	23.78	109.6	20.6
07 April 2021	2.70	2005 PU_{21}	36.86	2.6	18.9
08 April 2021	2.70	2005 PU_{21}	37.04	34.3	6.1
27 Feb. 2022	2.70	2007 RH_{283}	10.94	21.1	43.6

[a]Saturn–Jupiter–Neptune.

V_∞ are high. Direct Centaur encounter trajectories can have both shorter flight times and lower departure V_∞. Also, these direct Centaur encounter trajectories require no significant deterministic ΔV (i.e., they are, for all practical purposes, ballistic trajectories). Figures 13 and 14 show porkchop plots for trajectories to Chiron and BL_{41}, respectively. Orbits with the same period as Saturn (or twice as long in some cases) are shown with gray lines. If Cassini left Saturn to encounter a Centaur on one of these resonant orbits, Cassini would return to impact Saturn, decisively ending the mission, after one full revolution (or two revolutions for a two-to-one resonance) of Saturn around the sun. Because Saturn's orbital period is 29.5 years, the TOF after the Centaur encounter to reach Saturn is found by subtracting

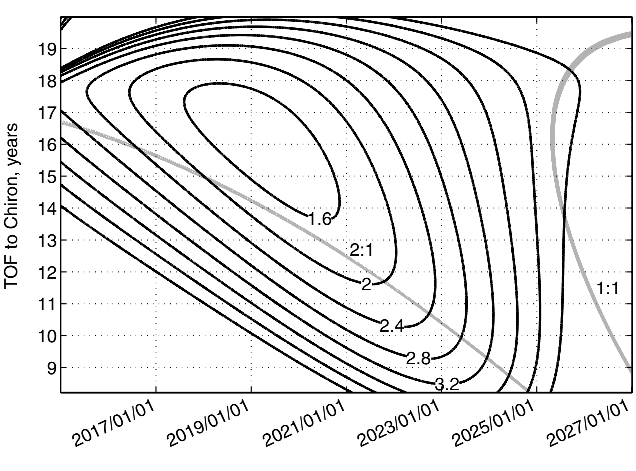

Fig. 13 Porkchop plot of launch windows from Saturn to Chiron; contours are Saturn departure V_∞ in kilometers per second with minimum $V_\infty = 1.38$ km/s, where the right gray line indicates one-to-one Saturn-resonant orbits and the left gray line indicates two-to-one Saturn-resonant orbits.

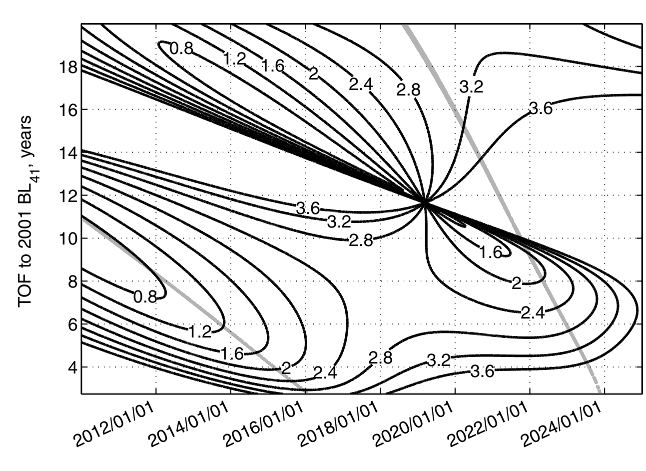

Fig. 14 Porkchop plot of launch windows from Saturn to 2001 BL_{41}; contours are Saturn departure V_∞ in kilometers per second with minimum $V_\infty = 0.44$ km/s, where the gray lines indicate one-to-one Saturn-resonant orbits.

Table 8 Centaur objects that Cassini could encounter

Centaur name	a, AU	e	i, deg	d, km
Chiron	13.709	0.380	6.9	163
Chariklo	15.828	0.173	23.4	259
Okyrhoe	8.373	0.307	15.7	45
1994 TA	16.729	0.304	5.4	22 [a]
1999 OX_3	32.353	0.455	2.6	192 [a]
1999 TZ_1	5.214	0.039	43.5	61 [a]
2001 BL_{41}	9.747	0.294	12.5	34
2002 PQ_{152}	25.733	0.200	9.4	84 [a]
2003 KQ_{20}	10.563	0.194	5.7	11 [a]
2003 LH_7	16.964	0.292	21.2	14 [a]
2003 QC_{112}	22.122	0.209	16.7	80 [a]
2003 QP_{112}	21.129	0.329	31.2	13 [a]
2005 CC_{79}	20.068	0.163	28.3	192 [a]
2005 PU_{21}	173.901	0.833	6.2	265 [a]
2007 RH_{283}	15.936	0.341	21.4	101 [a]

[a]Estimated diameter assuming an albedo of 0.09.

the Saturn-to-Centaur TOF from 29.5 years (in the case of a one-to-one resonance) or from 58.9 years (in the case of a two-to-one resonance).

Discussion

Here we briefly discuss some of the advantages and disadvantages (costs and benefits) of the Saturn escape options we have outlined. Although results that we have presented may have tantalizing appeal in terms of scientific return, we emphasize that they are based on preliminary feasibility studies with patched-conic models and therefore must be verified in higher fidelity models (e.g., via numerical integration).

The patched-conic model is an efficient way of rapidly exploring a vast design space and examining the feasibility of a large number of options. The conic approximation is sufficient to demonstrate the existence of these types of interplanetary, gravity-assist trajectories. Throughout this paper, we employ a zero-sphere-of-influence, patched-conic method, in which trajectories pass from body center to body center. The planetary states are drawn from an analytic ephemeris that accounts for orbital elements (i.e., eccentricity, inclination, etc.) and their rates of change. Patched-conic computation of TOF may overestimate the arrival time of an Earth-to-Jupiter trajectory by several days and of an Earth-to-Pluto trajectory by several weeks [22]. Such errors have no effect on judging the relative merits of the trajectories we report here.

There is no flyby-and-forget option for visiting the Centaurs. Because a deep space maneuver (ΔV) would be required, mission operations would need to be extended (increasing the cost of the mission). However, the scientific value of visiting a Centaur can be high, as no spacecraft has ever observed a Centaur and it would be expensive to develop a new mission for this purpose. It may be significantly cheaper to extend Cassini's mission to include a flyby of a Centaur than to develop a new mission (see Table 8 for a list of the orbital characteristics and approximate diameters of the Centaur objects that Cassini could potentially reach). On the other hand, the impact trajectories that terminate at Jupiter, Uranus, or Neptune are flyby-and-forget options: once the spacecraft leaves Saturn (or flies by a gas giant) and performs a final targeting maneuver, it will impact the next body without further correction. The operational feasibility of these trajectories will be affected by many factors, including propellant, power, communication, and funding, the details of which are beyond the scope of this analysis.

Finally, we note that aligning the line of apsides and pumping up the orbit to prepare for escaping the Saturnian system can take as long as 2 years. To account for this, the Saturn-escape scenario must be planned in advance, earlier than other Cassini end-of-mission scenarios (e.g., impacting Saturn's atmosphere).

Conclusions

Saturn escape offers several attractive options for the Cassini encore mission. A grand tour trajectory exists that encounters Jupiter, Uranus, and Neptune. The grand tour satisfies the planetary quarantine requirements by targeting each leg to impact at the destination planet if the spacecraft is no longer operable at time of arrival. A range of Saturn–Jupiter and Saturn–Uranus trajectories (within the envelope of Cassini's achievable departure V_∞) enables solar system escape after as little as 7 years for a Jupiter flyby and 13 years for a Uranus flyby. Flying Cassini into the sun via a gravity assist from Jupiter, Uranus, or Neptune, however, requires a larger Saturn departure V_∞ than Cassini can achieve. It is possible to fly Cassini by Uranus during its next equinox in 2049. Capturing Cassini into orbit around Jupiter (using any of the Galilean satellites) or at Neptune (using Triton) is possible from an energy perspective. Some of the largest and most well-known Centaurs are accessible to Cassini with its currently available departure V_∞ in as little as 3.5 years. Cassini can reach Chiron, the first-discovered Centaur, in 10.5 years after a 2022 Saturn departure.

Appendix

Figures A1–A4 show porkchop plots for trajectories from Saturn to Chariklo, Okyrhoe, 1999 TZ_1, and 2003 KQ_{20}.

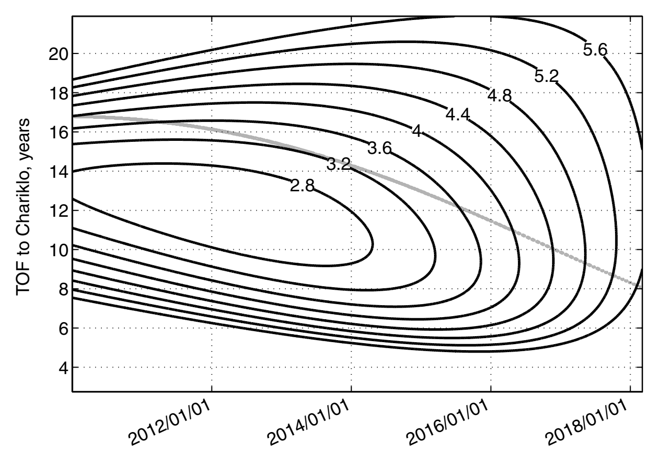

Fig. A1 Porkchop plot of launch windows from Saturn to Chariklo; contours are Saturn departure V_∞ in kilometers per second with minimum $V_\infty = 2.49\ \mathrm{km/s}$, where the gray line indicates two-to-one Saturn-resonant orbits.

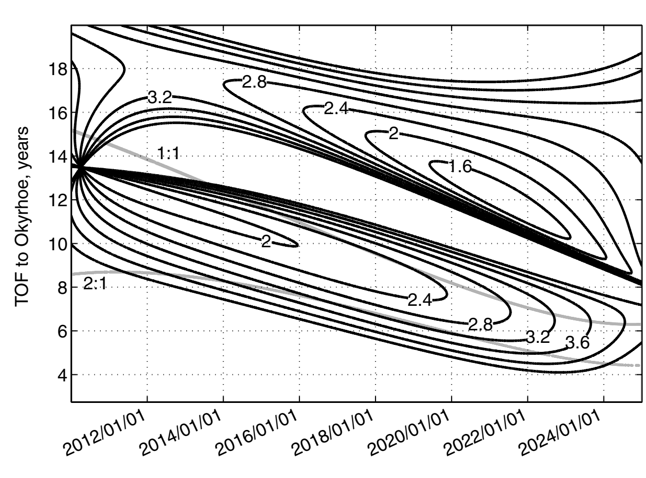

Fig. A2 Porkchop plot of launch windows from Saturn to Okyrhoe; contours are Saturn departure V_∞ in kilometers per second with minimum $V_\infty = 1.34\ \mathrm{km/s}$, where the top gray line indicates one-to-one Saturn-resonant orbits and the bottom gray line indicates two-to-one Saturn-resonant orbits.

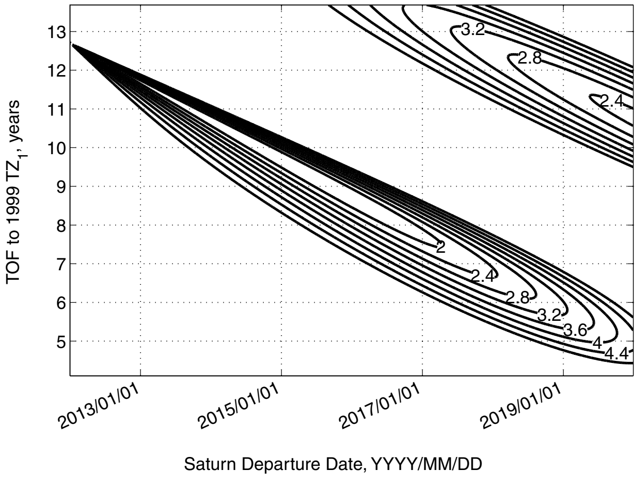

Fig. A3 Porkchop plot of launch windows from Saturn to 1999 TZ_1; contours are Saturn departure V_∞ in kilometers per second, with minimum $V_\infty = 1.63$ km/s.

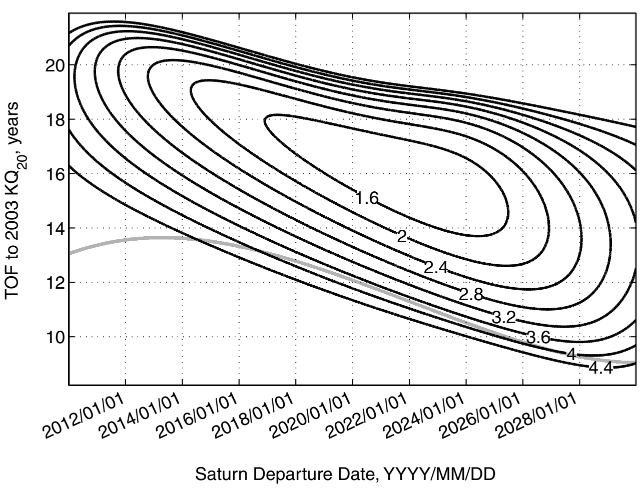

Fig. A4 Porkchop plot of launch windows from Saturn to 2003 KQ_{20}; contours are Saturn departure V_∞ in kilometers per second with minimum $V_\infty = 1.24$ km/s, where the gray line indicates one-to-one Saturn-resonant orbits.

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