The *Cassini* Mission's End Game At Saturn

Introduction

Launched on 15 October 1997, the *Cassini* spacecraft required gravity assists from Venus, Earth, and Jupiter before achieving Saturn orbit on 1 July 2004[1]. Since then, it has served as launch platform for the *Huygens* probe's historic landing on Saturn's major moon Titan[2], discovered briny water ice in geysers erupting from the moon Enceladus[3], imaged exotic moonlets within Saturn's rings[4], witnessed complex ring particle dynamics[5], monitored global storms in Saturn's atmosphere[6], confirmed hydrocarbon lakes dotting Titan's surface[7], and provided unique perspectives of Saturn[8] along with many more views and insights evoking our awe.

On 15 September 2017, *Cassini*'s 13-year tour of the Saturn system ends with incineration high in the planet's atmosphere. This disposal measure is in accord with NASA's forward planetary protection policy because *Cassini* is running out of propellant with which to control its trajectory. Disposing of the spacecraft in Saturn's atmosphere ensures it does not inadvertently crash onto Titan or Enceladus. Thanks to *Cassini*, both of these moons are now known to harbor subsurface liquid water oceans where extant life is possible.

Mission Planning Pedigree

Cassini trajectory data presented in this article are obtained from JPL's *Horizons* ephemeris server[9] in a posting dated 9 September 2015. Trajectory data generated 2 years beforehand are still valid for *Cassini* disposal because, as of 15 July 2017, the spacecraft had performed 360 of 492 planned trajectory correction impulses to preserve mission design[10]. In Saturn orbit, such control is made possible with remaining onboard propellant, together with some heavy lifting from gravity assists during Titan flybys. To demonstrate the precision of posted *Horizons* data, consider the following report from the 3 August 2017 "*Cassini* Spacecraft Update".

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Saturday, July 29 (DOY 210)

Early today Cassini coasted through apoapsis [or apochrone in this article], the
highest and slowest part of its orbit of Saturn. This marked the start of its
Saturn orbit #286 [or Orb 286 in this article].

As soon as the long ISS [Cassini's Imaging Science Subsystem] observation of
[Saturn's small irregular moon] Kiviuq was done, it was time for Kappa Orionis to
re-emerge from behind Saturn's atmosphere, this time in the sunlit north. UVIS
[Cassini's Ultraviolet Imaging Spectrograph] watched it for another 70 minutes as
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[1] Reference https://saturn.jpl.nasa.gov/resources/1776/ (accessed 7 August 2017).
[2] Reference https://saturn.jpl.nasa.gov/resources/2958/ (accessed 7 August 2017).
[3] Reference https://saturn.jpl.nasa.gov/resources/4852/ (accessed 7 August 2017).
[4] Reference https://saturn.jpl.nasa.gov/resources/7695/ (accessed 7 August 2017).
[5] Reference https://saturn.jpl.nasa.gov/resources/2570/ (accessed 7 August 2017).
[6] Reference https://saturn.jpl.nasa.gov/resources/5329/ (accessed 7 August 2017).
[7] Reference https://saturn.jpl.nasa.gov/resources/5959/ (accessed 7 August 2017).
[8] Reference https://photojournal.jpl.nasa.gov/catalog/PIA08329 (accessed 7 August 2017).
[9] Reference https://ssd.jpl.nasa.gov/?horizons (accessed 7 August 2017).
[10] Reference https://saturn.jpl.nasa.gov/news/3096/one-final-burn/ (accessed 11 August 2017).

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it re-appeared. This blue star is well known as the lower-left star in the
constellation Orion's main quadrangle. It can be seen beginning to egress from
Saturn occultation, in this simulated view from Cassini:
https://go.nasa.gov/2uS8j6b.
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The JPL rendering of Kappa Orionis (*κ Ori*) egress, as accessed with the "*Cassini* Spacecraft Update" link, is reproduced in Figure 1 for comparison purposes.

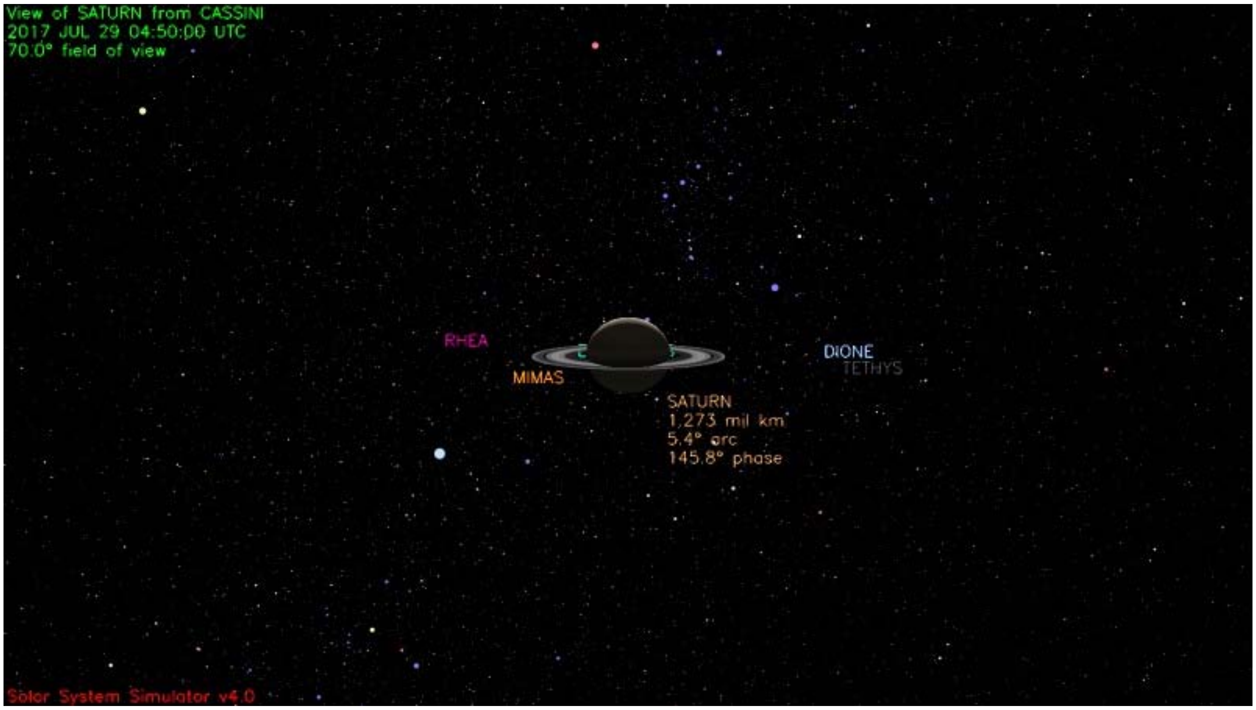

Figure 1. The contemporaneous JPL rendering of *κ Ori* egress from Saturn as observed by *Cassini* on 29 July 2017 at 04:50:00 UTC is reproduced from its posting to URL https://go.nasa.gov/2uS8j6b (accessed 9 August 2017). The rendering shows this egress near the 1 o'clock position on Saturn's limb.

The same stellar egress is rendered with *Celestia*[11] software in Figure 2 using *Cassini* trajectory data imported from *Horizons*. *Celestia* rendering of Saturn in Figure 2 is considerably brighter than in Figure 1 in order to reproduce easily visible stars. Positioning of those stars with respect to Saturn in Figures 1 and 2 is identical at the scale for these renderings. Consequently, the two figures serve to illustrate a high degree of correlation between the *Cassini* trajectory being flown in the real world and that posted to *Horizons*.

[11] Reference https://celestiaproject.net/ (accessed 7 August 2017).

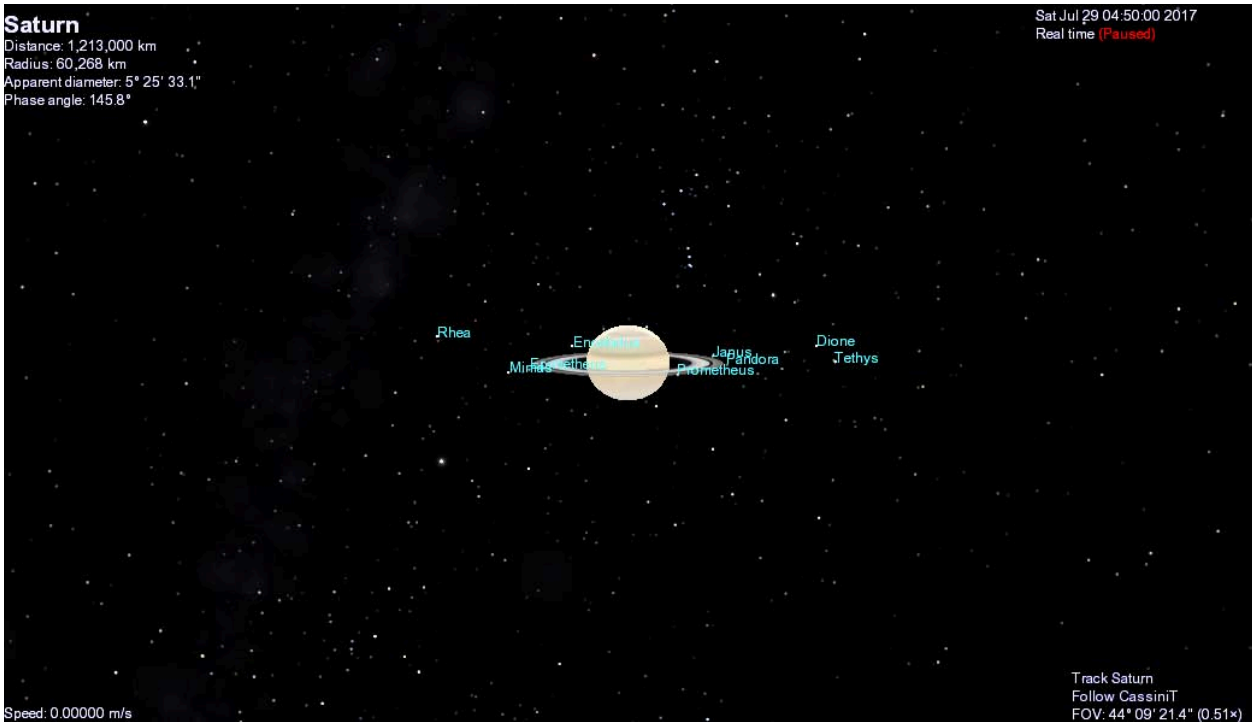

Figure 2. *Celestia* renders the Figure 1 *κ Ori* egress using imported *Cassini* trajectory data posted to *Horizons* 2 years earlier. Note stars and moons are independently positioned with respect to Saturn exactly as they are in Figure 1.

Enabling *Cassini* Mission Objectives With Titan Gravity Assists

Throughout *Cassini*'s sojourn in Saturn orbit, Titan gravity assists enable a broad spectrum of scientific observations. Thanks to Titan's gravity, dramatic changes in *Cassini* orbit inclination with respect to Saturn's equator, minimal orbit distance from Saturn (perichrone), orbit period, and apochrone/perichrone orientation with respect to the Sun/Saturn line are possible with relatively miniscule propellant consumption.

Since Titan orbits Saturn at an inclination of 0.28° and a distance near 1.2 million km, persistent Titan flybys require *Cassini* to maintain one of its orbit plane nodes on Saturn's equatorial plane near 1.2 million km. As illustrated in Figures 1 and 2, other moons of Saturn and ring particles orbit the planet at low inclinations too. When *Cassini*'s orbit inclination is also low, close observations of moons other than Titan can then be planned. The scientific downside to low orbit inclinations is *Cassini* can only view Saturn's rings edge-on, as illustrated by Figure 3.

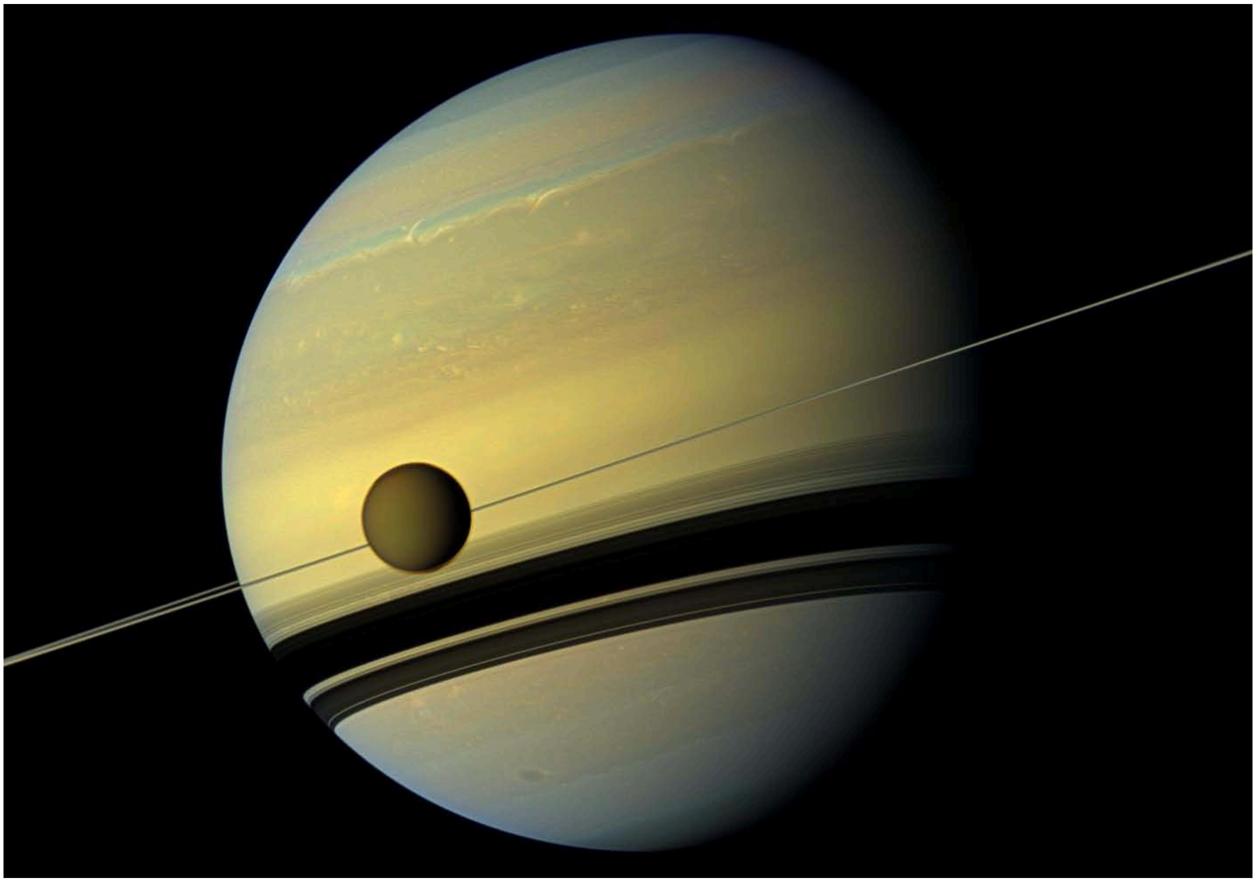

Figure 3. *Cassini* observes Titan on 6 May 2012 from a distance of 778,000 km as the moon (5151 km in diameter) transits Saturn. Note the barely visible edge-on rings behind Titan and their shadows cast onto the planet. These shadows are nearly impossible to observe from Earth because our planet's Saturn perspective differs little from the Sun's. Reference https://saturn.jpl.nasa.gov/resources/5631/ (accessed 9 August 2017).

Many Titan flybys (each designated with a "T-nnn" code, where "nnn" is a chronologic integer) are primarily dedicated to altering *Cassini* orbit inclination. Over time, these gravity assists provide a balance between observations only possible at low inclinations and those only possible at high inclinations. Figure 4 illustrates how such inclination changes are accomplished from 2016 until *Cassini* disposal.

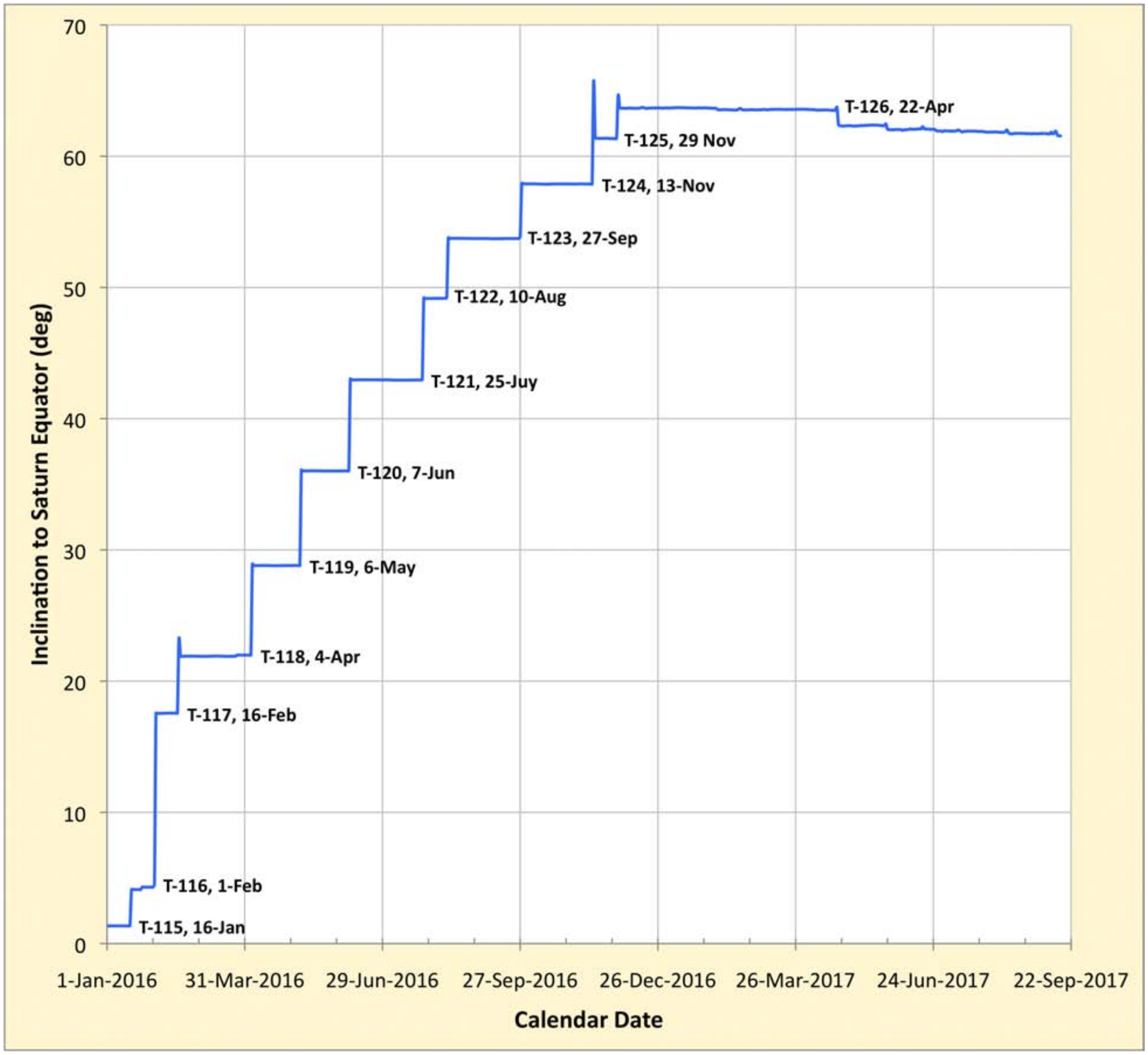

Figure 4. *Cassini* orbit inclination with respect to Saturn's equator is plotted as a function of UT from 1 January 2016 until spacecraft incineration on 15 September 2017. Inclination is typically incremented or decremented during each Titan flyby (annotated with a "T-nnn" chronologic counter) to a degree far beyond the capability of *Cassini* propulsion alone. Plot data are at 1-day intervals, and "spikes" can arise when an inclination value is obtained *during* a Titan gravity assist. Similar features arise in Figures 5 and 6.

As Titan flybys alter *Cassini*'s orbit, different observations become possible with greater clarity. In this process, however, perichrone must be carefully constrained to avoid collisions with ring particles orbiting at a similar distance from Saturn. Figure 5 demonstrates the perichrone ring avoidance strategy during 2016 and 2017.

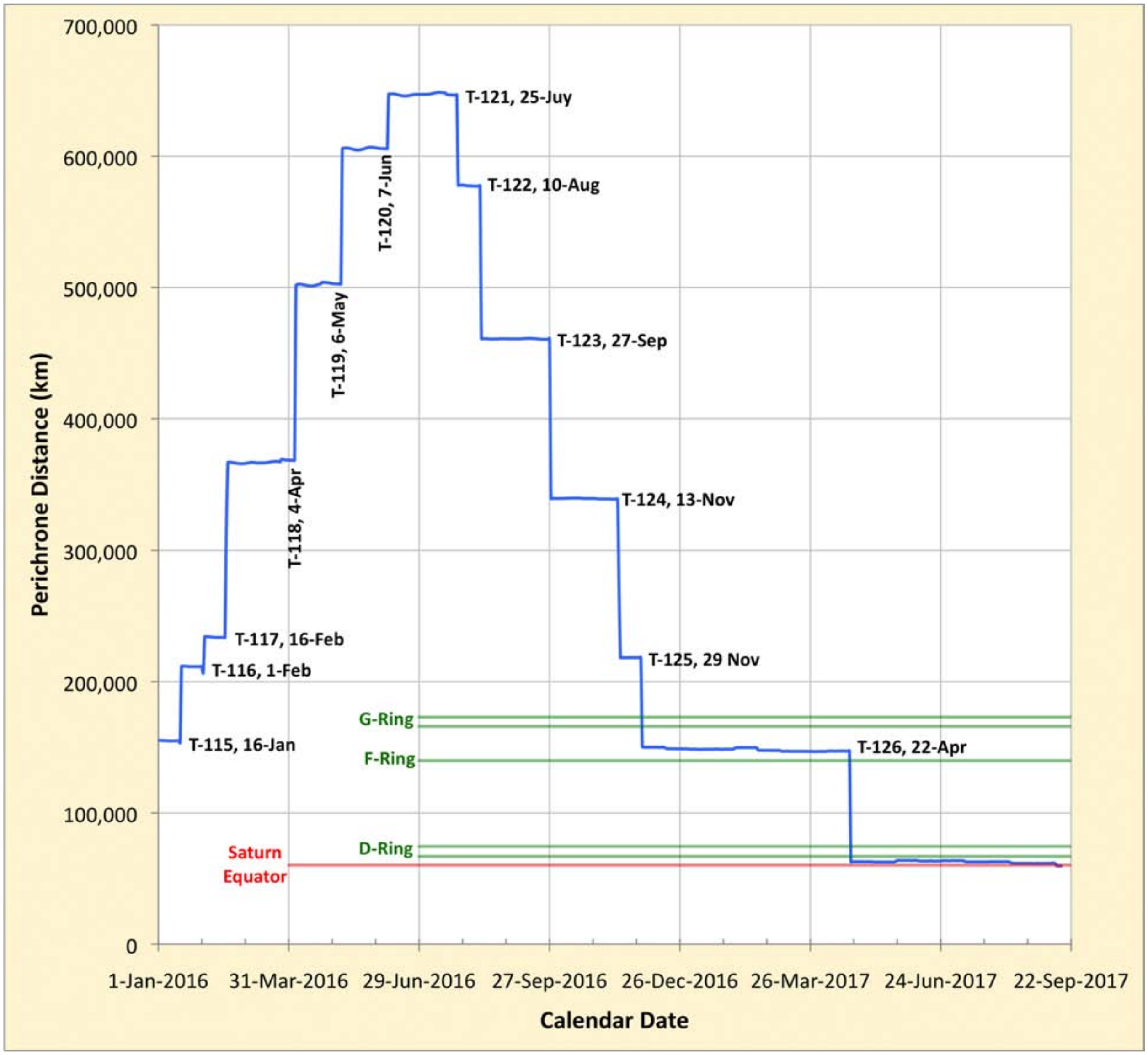

Figure 5. *Cassini* perichrone distance from Saturn's center is plotted as a function of UT (blue) from 1 January 2016 until spacecraft incineration on 15 September 2017. Note how perichrone avoids regions about Saturn in which ring particles orbit, as annotated in green, thereby evading high-probability collisions. The red Saturn Equator annotation is at a distance of 60,268 km, where the planet's equatorial atmospheric pressure is 1 bar.

Achieving a practical cadence of gravity assist flybys with reasonable propellant consumption requires *Cassini* maintain an orbit period resonance with Titan. Each resonance is expressed with $j{:}k$ notation in which *Cassini* makes j complete orbits of Saturn in the same time Titan makes k complete orbits of Saturn with a fixed period of 15.945 days. Implementation of this strategy is illustrated in Figure 6.

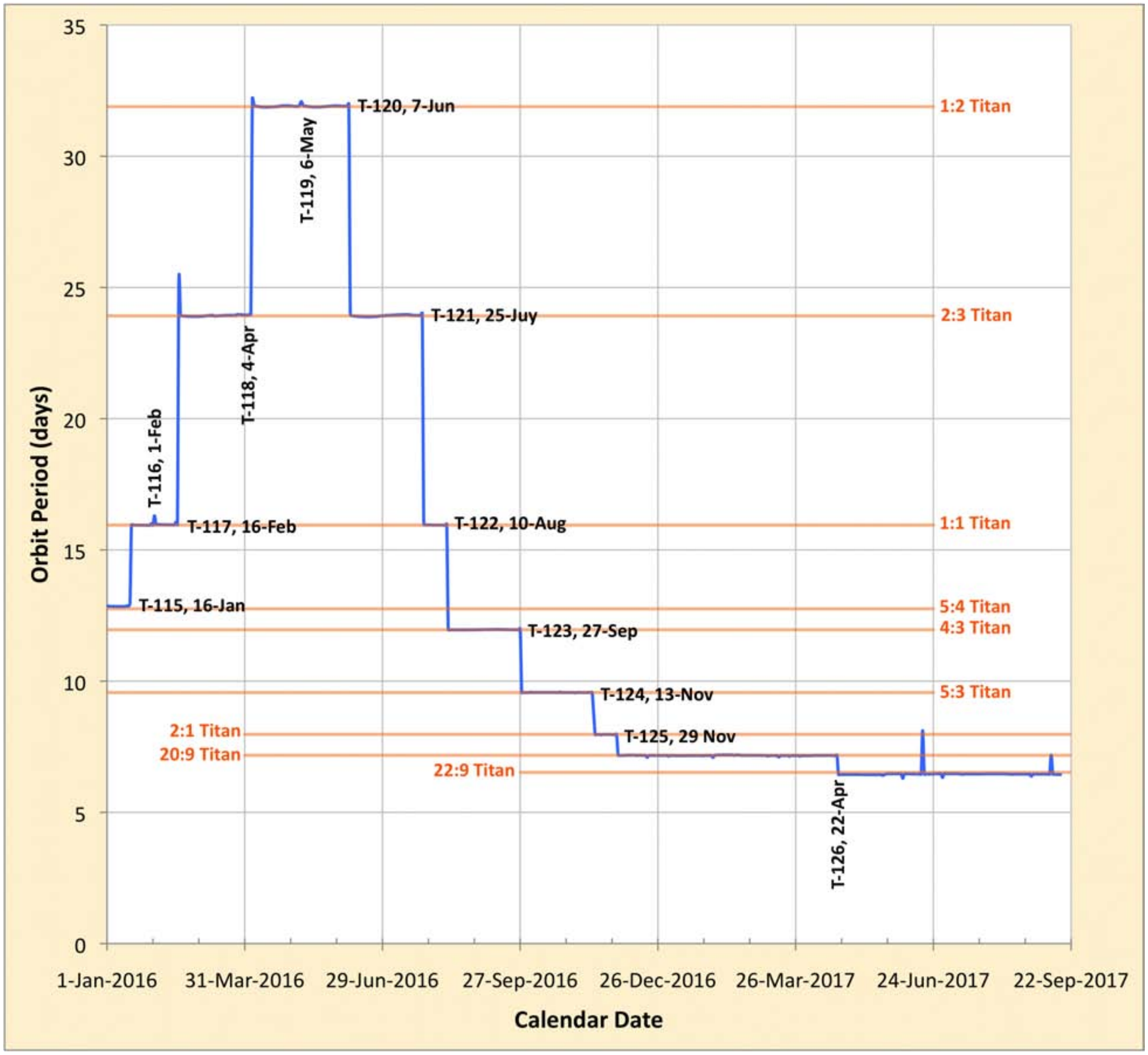

Figure 6. *Cassini* orbit period is plotted as a function of UT (blue) from 1 January 2016 until spacecraft incineration on 15 September 2017. To maintain a practical cadence of Titan gravity assists in support of mission objectives, a variety of orbit period resonances must be achieved between *Cassini* and Titan as annotated in orange.

Cassini's Grand Finalé

Per Figure 5, the T-126 flyby on 22 April 2017 causes perichrone to jump from immediately outside Saturn's major rings to a distance just inside them. This gravity assist initiates the mission's Grand Finalé phase with *Cassini* plunging 22 times between Saturn's atmosphere and its innermost D-Ring at 61.8° inclination[12]. Effects of the T-126 gravity assist on *Cassini* Saturn-centered motion are shown in Figure 7.

[12] Details on each Grand Finalé orbit can be found at https://saturn.jpl.nasa.gov/mission/grand-finale/grand-finale-orbit-guide/ (accessed 13 August 2017).

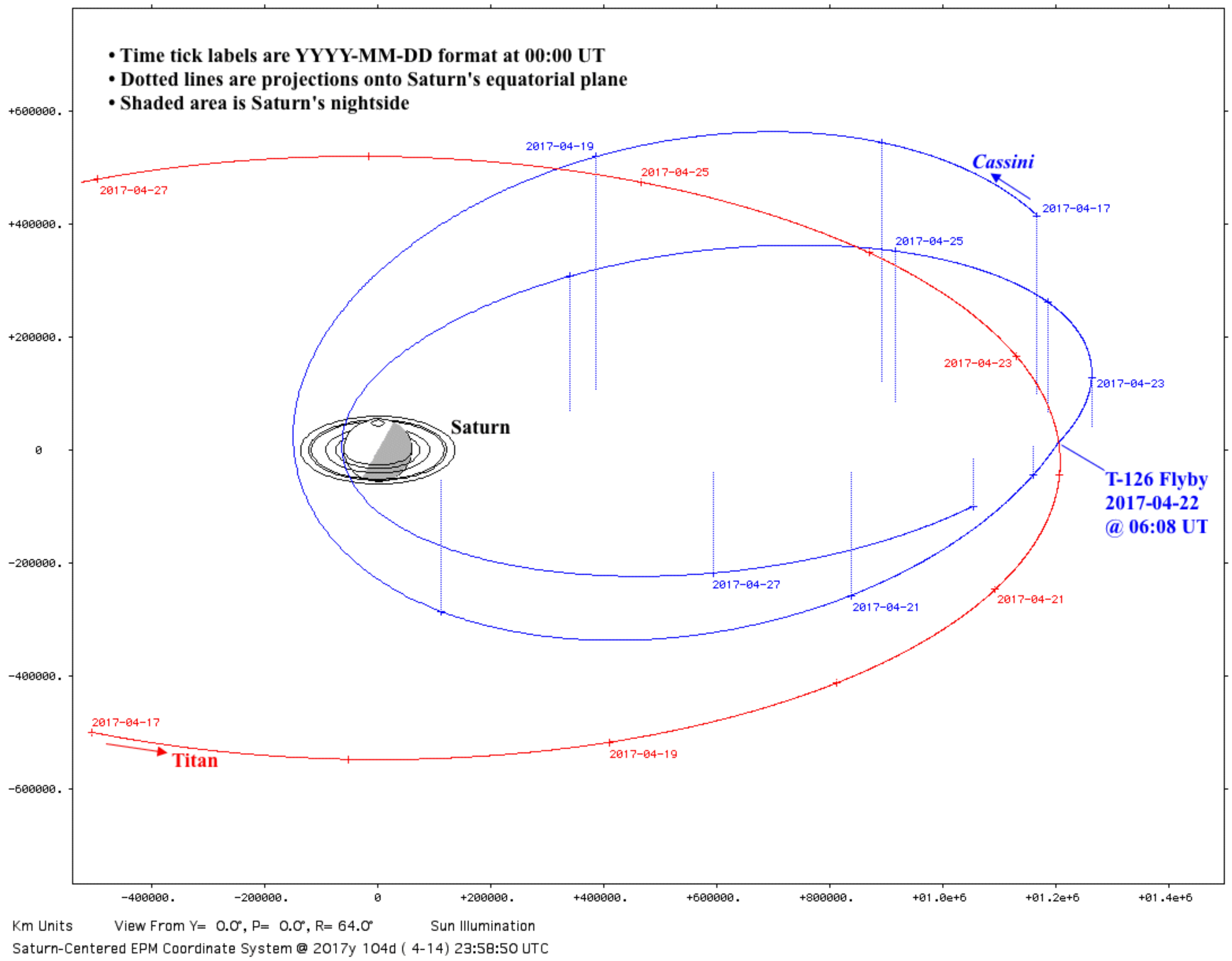

Figure 7. Saturn-centered motion of Titan (red) and *Cassini* (blue) are plotted immediately before and after the T-126 flyby. The associated Titan gravity assist shifts perichrone from outside Saturn's major rings to inside them and less than 3000 km above a level in Saturn's atmosphere with 1 bar pressure. When *Cassini* reaches apochrone shortly after T-126, Orb 271 and the Grand Finalé phase begin.

Figure 8 illustrates a *Cassini* view of the rings and Saturn as the 14th Grand Finalé perichrone plunge begins at the start of Orb 284.

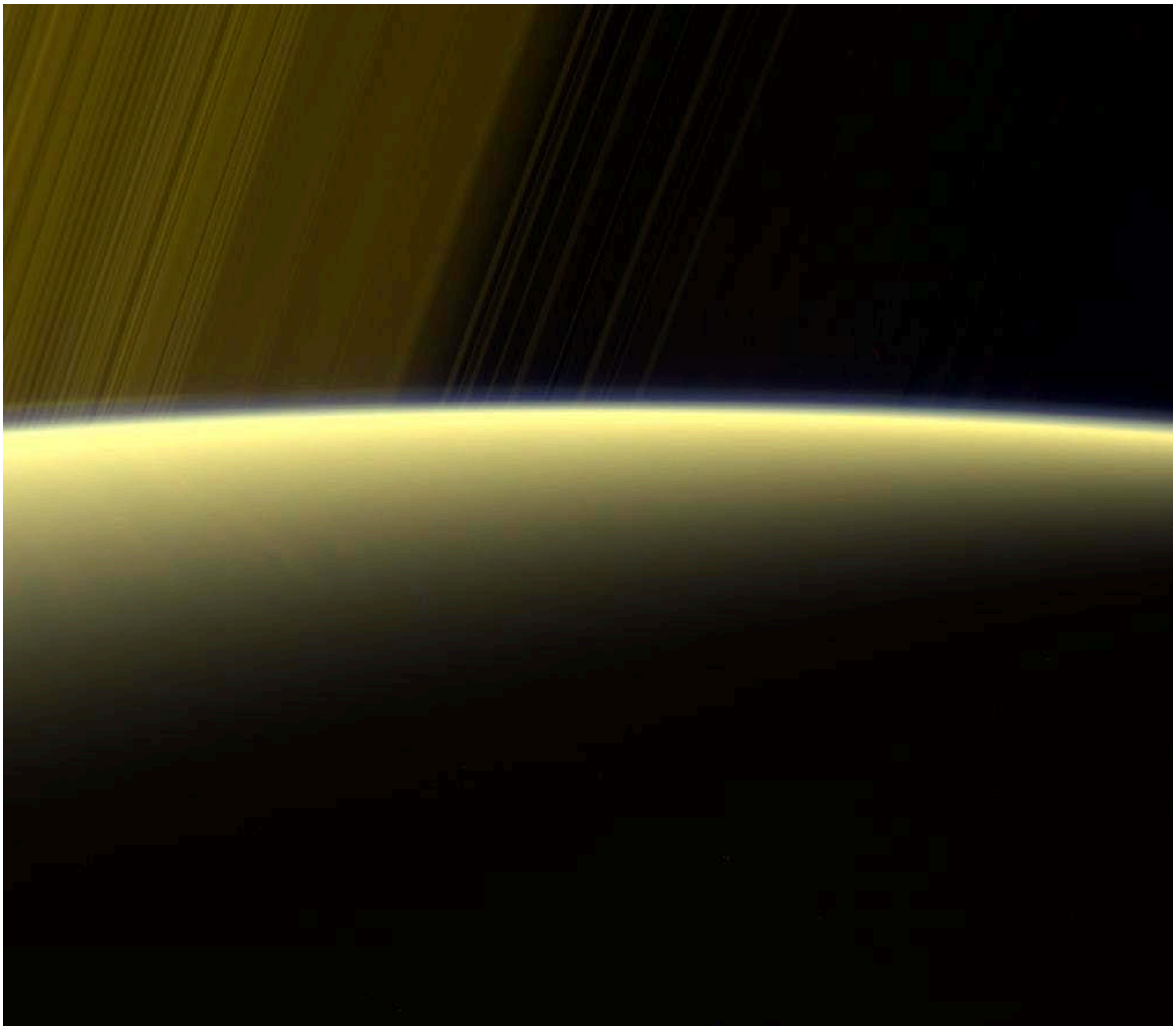

Figure 8. After commencing Orb 284 at 1.25 million km from Saturn on 16 July 2017, *Cassini* captures the planet's upper atmosphere partially backlit by its rings as the spacecraft begins its plunge to the 14th Grand Finalé perichrone. Note the detached haze layer in Saturn's stratosphere. On 15 September 2017, during its 23rd Grand Finalé perichrone passage, *Cassini* loses attitude control and breaks contact with Earth above this layer shortly before atmospheric friction incinerates the spacecraft. Reference https://saturn.jpl.nasa.gov/resources/7716/ (accessed 9 August 2017).

As plotted in Figure 6, the T-126 gravity assist places *Cassini* in a 22:9 orbit period resonance with Titan. Although T-126 is *Cassini*'s last close approach to Titan, Figure 9 indicates multiple encounters of the moon arise during the Grand Finalé. When these encounters attain *Cassini*-Titan range near 100,000 km, appreciable gravity perturbations are exerted on the spacecraft's Saturn orbit. The last 5 perichrone passages prior to *Cassini*'s incineration (those on Orb 288 through Orb 292) are briefly inside Saturn's atmosphere, less than 1800 km above the 1 bar pressure level. As the post-T-126 resonance plays out after 22 Grand Finalé orbits by *Cassini*, a Titan encounter to within 123,000 km occurs on 11 September 2017 at the end of Orb 292.

Informally known as "the goodbye kiss", gravity perturbations from this Titan encounter lower perichrone to a point *Cassini* incinerates in Saturn's atmosphere on Orb 293.

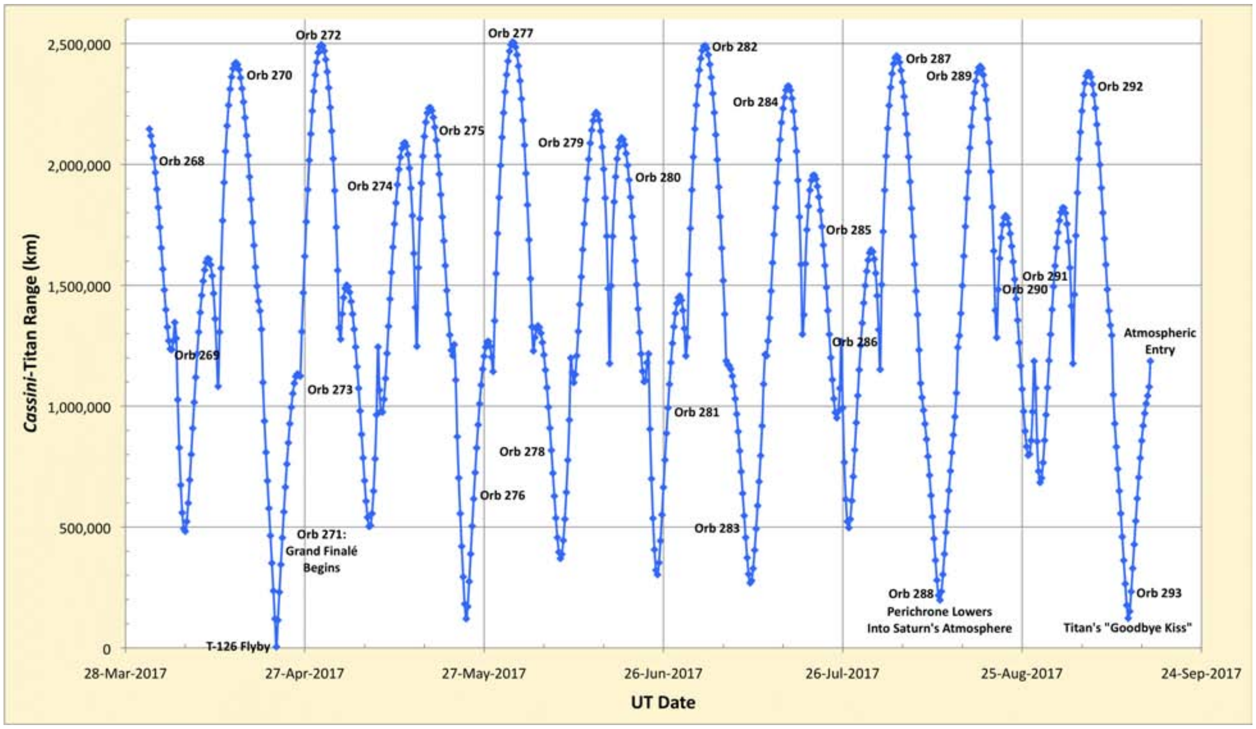

Figure 9. ***Cassini*** **range from Titan is plotted as a function of UT at 6-hour intervals from 1 April 2017 until final entry into Saturn's atmosphere on 15 September 2017. "Orb" annotations mark the start of each *Cassini* orbit as incremented at apochrone.**

During the Grand Finalé, *Cassini* is able to make observations of a quality not possible earlier in the mission. Higher resolution imagery of Saturn's north polar vortex and hexagonal jet stream[13] are obtained, while the planet's southern aurora is accessible to the spacecraft for detailed photography[14]. Doppler shifts measured in *Cassini*'s radio link with Earth significantly refine mass estimates for Saturn's rings and variations in the planet's gravity field. Magnetometer readings directly determine Saturn's rotation rate, a parameter previously inferred from cloud observations subject to ambiguous atmospheric wind and convection influences. Near perichrone, direct sampling of inner ring particles and Saturn's uppermost atmosphere are made to determine their composition.

Because the rings and planet subtend relatively large angles throughout *Cassini*'s Grand Finalé orbits, a greater number of stars can be observed to pass behind them. Measuring variations in starlight intensity at multiple wavelengths during an occultation provides valuable insights such as atmospheric pressure versus height (per the *κ Ori* occultation reproduced in Figure 1) and particle size distributions/densities in the rings. Related insights are made when *Cassini*'s radio transmissions are received on Earth after passing through Saturn's atmosphere or rings.

[13] Reference https://saturn.jpl.nasa.gov/resources/5805/ (accessed 13 August 2017).
[14] Reference https://saturn.jpl.nasa.gov/resources/7720/ (accessed 13 August 2017).

Figure 10 illustrates *Cassini* Saturn-centered motion during most of its last complete orbit, Titan's goodbye kiss, and final entry into the planet's atmosphere. Atmospheric forces are expected to result in loss of attitude control and communications with *Cassini* at 10:45 UT on 15 September 2017, about a minute after entry. These final signals will be received on Earth 83 minutes later at 12:08 UT. Requiem, *Cassini*!

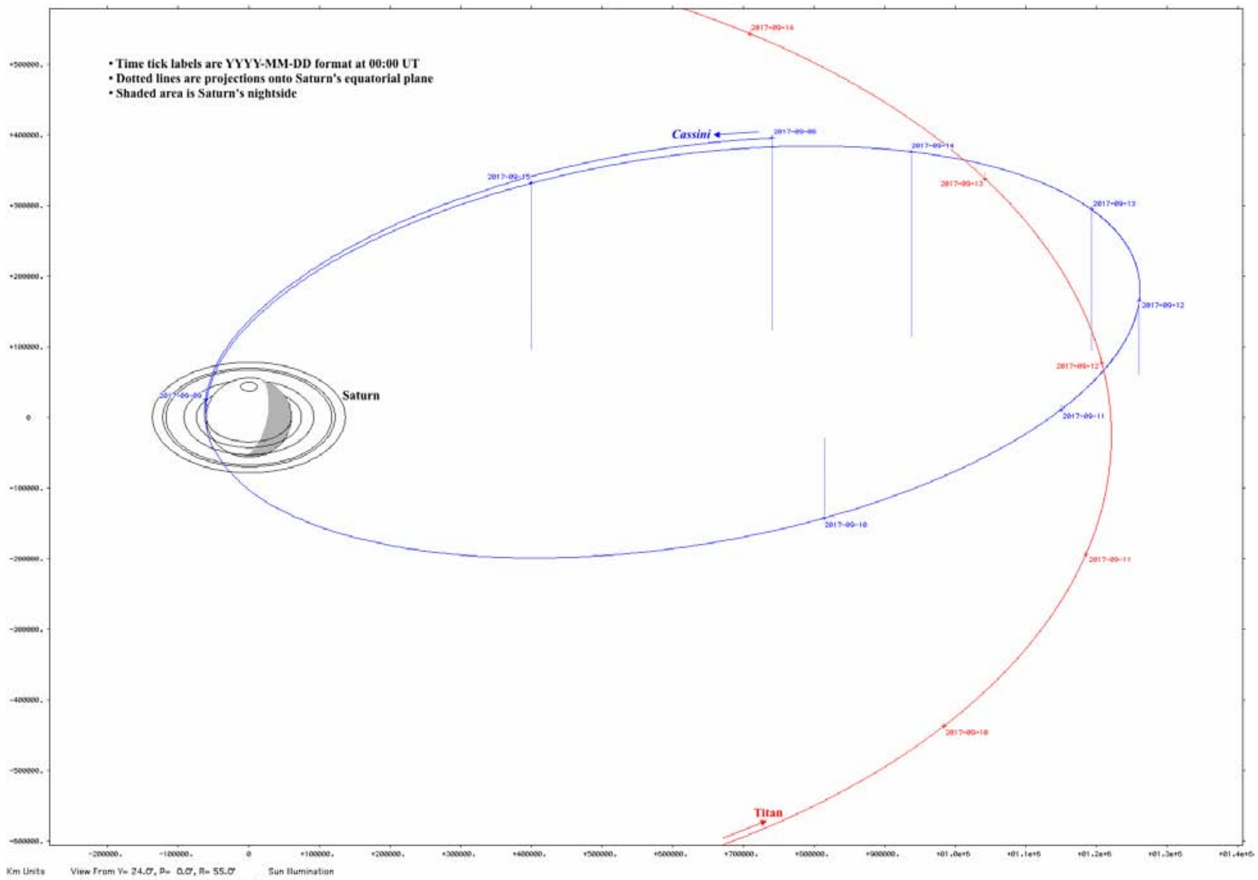

Figure 10. Saturn-centered motion of *Cassini* (blue) is plotted from 8 September 2017 until 10:44 UT on 15 September 2017, only minutes before incineration, when the spacecraft enters Saturn's atmosphere for the final time on Orb 293. Motion of Titan (red) is also plotted during part of this interval as it encounters *Cassini* to trigger the spacecraft's disposal.