A Conceptual Saturn Ring Observer Mission Using Standard Radioisotope Power Systems

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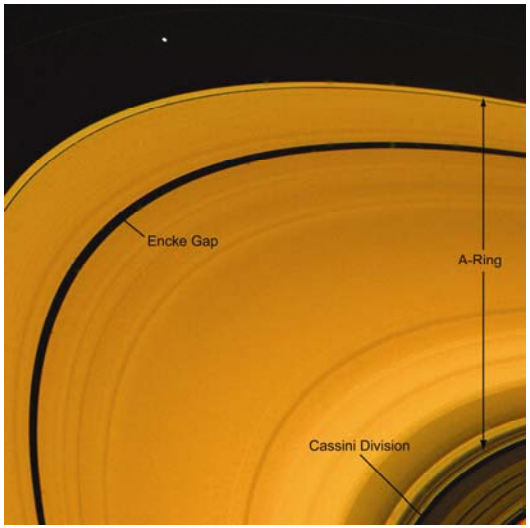
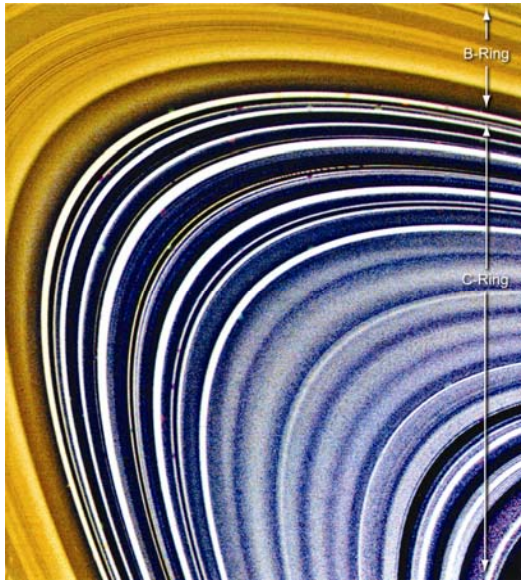
Introduction

- This concept study describes a conceptual Saturn Ring Observer (SRO) mission that would spend one year in close proximity to Saturn's A and B rings.
- Detailed observations and measurements of the rings and shepherding moons would be performed to achieve the goals of the NRC's Solar System Exploration Decadal Survey.
- Co-orbiting operations very close to the ring plane (as little as 1 km separation) would provide a vantage point unprecedented in solar system exploration.
- The primary objective of the mission would be to understand ring dynamics, including the microphysics of individual particles and small scale (meters to a few kilometers) phenomena such as particle agglomeration behavior.
- This would be accomplished by multispectral imaging of the rings at multiple key locations within the A and B rings, and by ring-particle imaging at an unprecedented resolution of 0.5 cm/pixel.
- SRO would be a valuable follow-on mission to Cassini-Huygens and would utilize RPS technology to enable its 11-year mission duration



Detail of Saturn's A Ring



Detail of Saturn's B and C Rings

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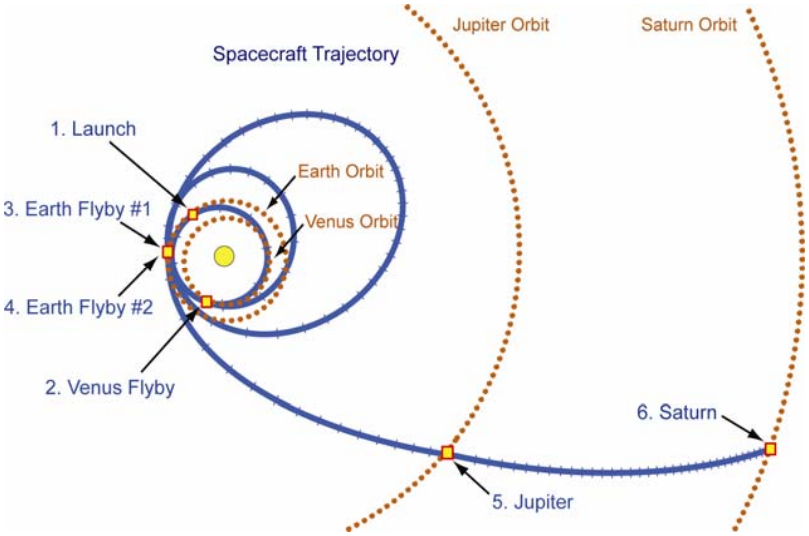
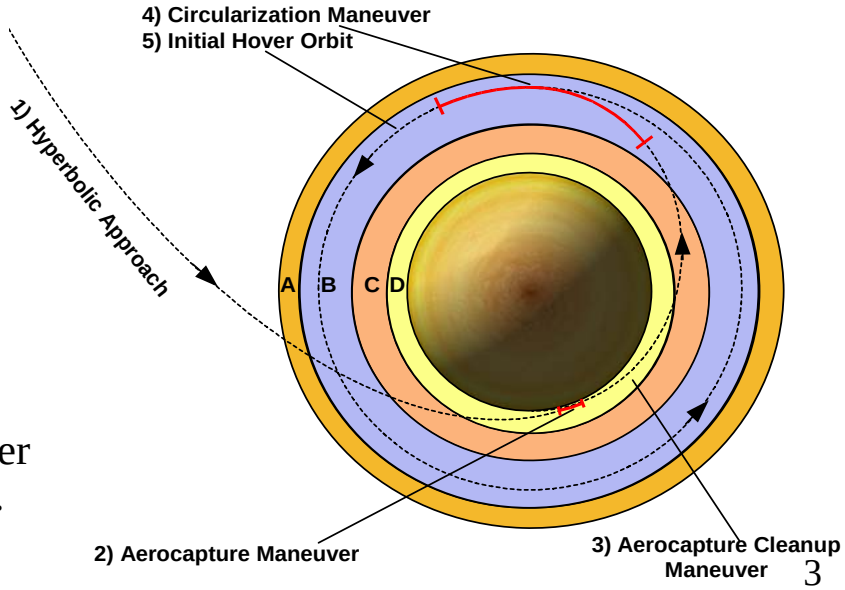
Mission Architecture

- This concept baselines a Venus-Earth-Earth-Jupiter Gravity Assist (VEEJGA) trajectory.
- This would be followed by aerocapture into Saturn orbit using an advanced aeroshell design.
  - Aerocapture permits a much larger delivered payload mass fraction into Saturn orbit compared with chemical propulsive insertion.
- To insert into Saturn orbit, the spacecraft would enter Saturn's stratosphere performing an aerocapture maneuver into an elliptical orbit.
- The aeroshell would be jettisoned following aerocapture, and the Propulsion stage would perform an aerocapture clean-up maneuver.
- Half a revolution later (~2 hrs), at apoapse, the Propulsion stage would perform a large ΔV maneuver to circularize the S/C orbit beside Saturn's B-Ring, slightly inclined to the ring plane (~0.0007º).
- Following circularization, the Propulsion stage would be jettisoned and the self-contained Orbiter would commence the year-long science mission.





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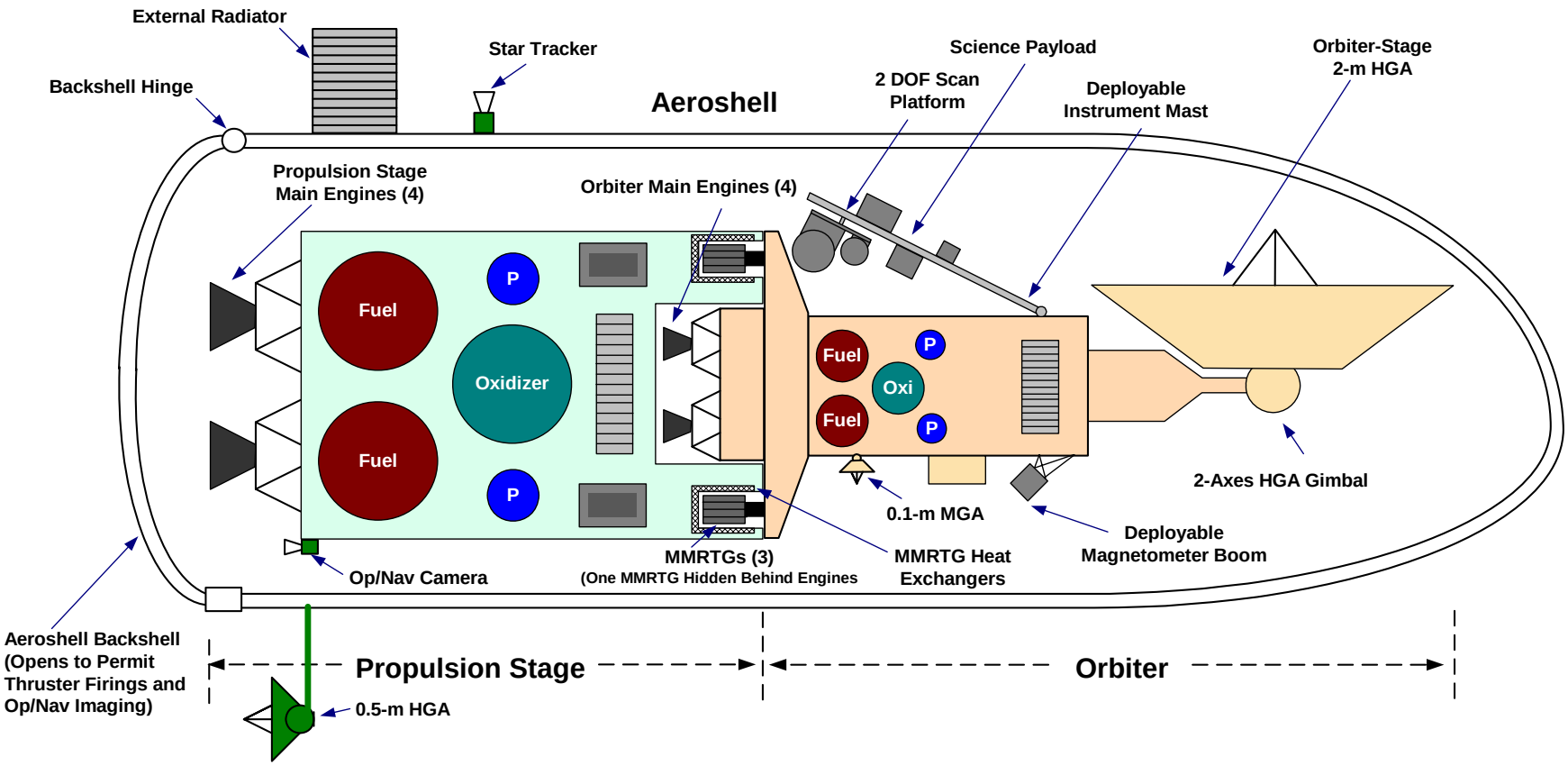
Conceptual Illustration of the SRO Spacecraft



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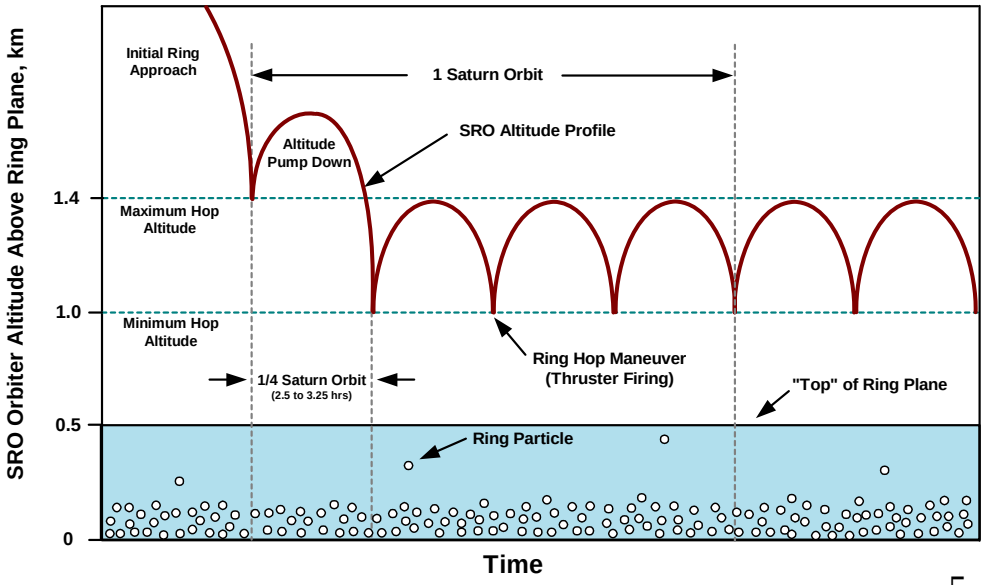
Mission Architecture

- Once in orbit, the SRO would stand off from the ring plane 1 to 1.4 km using chemical thrusters to provide short propulsive maneuvers four times per revolution to prevent ring plane crossings (and potential collisions with ring particles!).
- The spacecraft would effectively appear to “hop” above the ring plane every 2.5 to 3.25 hours depending on radial position.
- The Orbiter would stay at each selected radial position for an average of one week, co-orbiting with the ring particles to allow long-term observation and tracking of particle interactions and dynamics.
- At the end of the week, the Orbiter would perform a quasi-Hohmann transfer to the next target location, increasing its distance from Saturn each time.
- Detailed observations of the Saturn ring system would begin with the B ring at 110,000 km, and finishing with the A ring at 128,000 km at the end of one year.
- The Orbiter would nominally carry enough fuel for 1 year’s worth of “hopping”.



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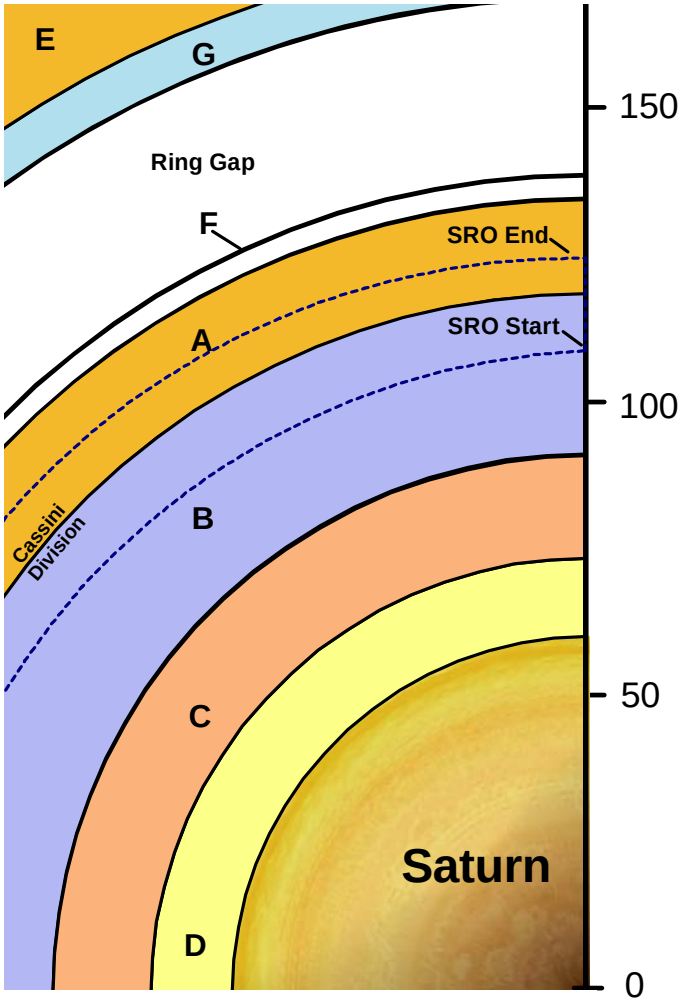
Mission Architecture

- The SRO concept envisioned here would require a next generation heavy launch vehicle (LV) to perform the mission assuming only a single launch vehicle was used.
- Trades were also performed to assess the minimal science payload and mission duration that could be supported by a single existing LV (e.g., Delta IV-H and Atlas V-551);
  - The preliminary conclusion was that a larger LV was required to launch any scientifically justifiable variant of the SRO spacecraft (were a single LV to be used.)
- The SRO launch vehicle is assumed to have a lift capability of ~22,640 kg to a C3 of 15 km2/s.
  - This is equivalent to the LV designs originally considered for Prometheus-One applications based on EELV-derived concepts.
- It is possible that the SRO could be launched in multiple sections using existing LVs and then assembled in Earth orbit.
  - This option was not explored in detail during this study.



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Science Goals

- The mechanisms of formation and evolution of planetary ring systems are poorly understood. These processes are of considerable scientific interest, as planetary ring systems are thought to share some characteristics with protoplanetary disks.
- The key unknowns of protoplanetary disk evolution involve the collisional dynamics of the particles and its effects on the collective behavior of the rings, especially evolution.
- The goal of the SRO mission would be to obtain close-in observations of centimeter-scale ring particle interactions to better understand these processes.
- The primary objective of the mission would be to observe and quantify ring particle properties at multiple key locations within the A and B rings.
- Individual ring particle properties to be investigated include particle sizes, particle shapes, rotation states, compositions, 3-d random velocity components, and surface textures.
- Two-particle investigations would focus on collision dynamics and collision frequency.
- Bulk and aggregate characteristics to be measured would include gross ring structure, particle density and surface mass density profiles (respectively, the number of particles and the total mass per unit area of ring surface), particle size distributions and spatial variation of size distribution at multiple ring locations, ring and ringlet thickness, layering and banding, wave characteristics, shepherding (e.g., by moons or moonlets) processes, and the neutral and ionized “ring atmosphere” environment.
- Lastly it would be important to characterize the electromagnetic environment near the rings and its relationship to ring structure and dynamics.

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Strawman Payload

Instrument	Purpose	Science Objectives Addressed
1. Narrow Angle Camera	Obtains images of individual ring particles and other objects at a resolution of 0.5 cm/pixel	Collision dynamics; Behavior of particle agglomerations; Particle geometry; Particle and mass density profiles; Particle size distributions; Particle random velocity components; Ring vertical structure; Shepherding moon observations
2. Wide Angle Camera	Obtains larger-scale images of larger ring particles, moons, and rings as aggregates of particles	Particle geometry; Particle and mass density profiles; Particle size distributions; Ring vertical structure; Shepherding moon observations; Particle random velocity components; Behavior of particle agglomerations; Context for NAC images
3. Visible and Infrared Spectrometer	Obtains high-resolution aggregate spectra of ring particles at visible and IR wavelengths	Particle elemental and mineralogical composition Ring structure (variation of composition with location) Composition of moons
4. Ion and Neutral Mass Spectrometer (INMS)	Obtains mass spectra of neutral and ionized species near the rings	Particle elemental and mineralogical composition Composition and structure of the “ring atmosphere”.
5. Magnetometer	Measures magnetic field strength and direction near the rings	Measures the static and quasi-static magnetic environment of the rings to investigate possible connections between ring structures and magnetic phenomena.
6. E-Field meter/Plasma Wave Spectrometer	Measures E-field strength and direction near rings, and plasma waves	Measures the static and quasi-static electric field environment of the rings to investigate possible connections between ring structures and electric fields.
7. LIDAR	Measures out-of-plane components of ring particle position and velocity	Provides the 3rd dimension of position and velocity needed for dynamics analyses. Also serves engineering function of determining distance to the ring plane for controlling thrusters.
8. Dust Detector	Measures the micrometeoroid flux near the rings	Determine rates and energies of micrometeoroid impacts on ring particles.

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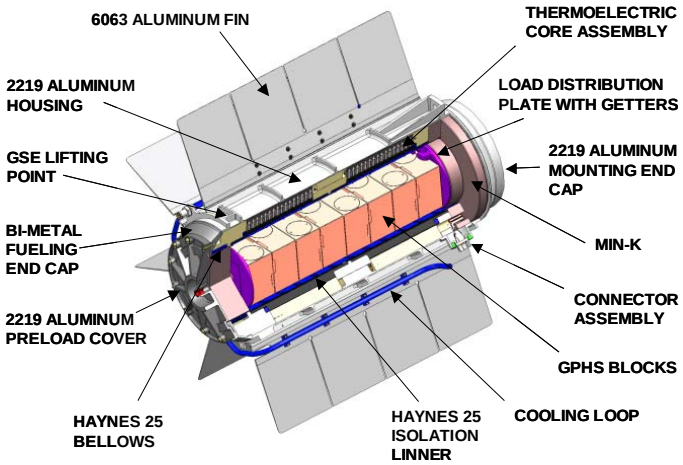
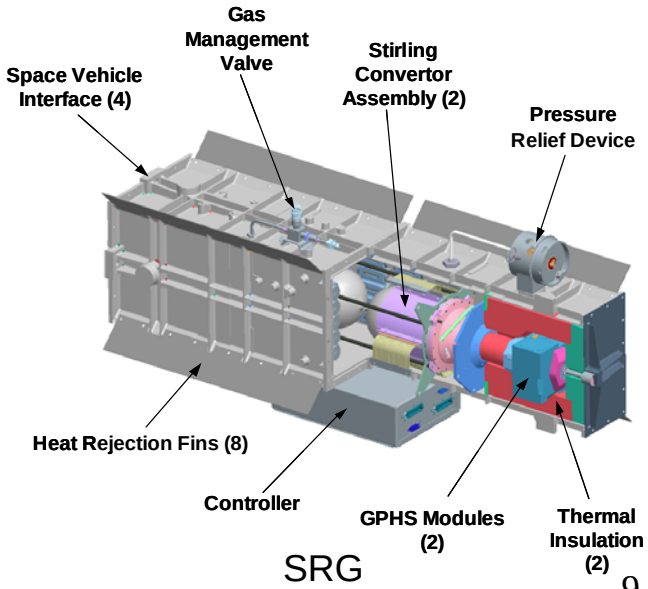
Radioisotope Power Systems

- Two RPS systems considered for SRO study:
- Multi-mission Radioisotope Generator (MMRTG)
  - Each MMRTG was assumed to generate ≥110 We at BOM with a conversion efficiency of ~6.3%, and have a mass of <45 kg.
  - The reference SRO spacecraft would use three MMRTGs to power all onboard systems, providing a minimum of ~275 We at EOM (after 11 years).
  - The ~5200 Wt (EOM) of residual heat would be used to maintain operational and survival temperatures of the Propulsion stage and Orbiter using radiatively coupled heat pipes.
- Stirling Radioisotope Generator (SRG)
  - Each SRG was assumed to produce ≥ 110 at BOM with a conversion efficiency of ~23%, have a mass of ~34 kg, and a specific power of ~3.4 We/kg.
  - A total of four units would be required in order to generate the requisite power and to provide one redundant SRG.
  - However, the lighter SRG means that the overall SRG system mass is ~ the same mass as the MMRTG option.
  - It is expected that higher efficiency of the SRG would be preferred during aerocapture when all heat would need to be stored (e.g., using phase change material).



MMRTG



SRG

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Power (1 of 2)

- The SRO spacecraft would employ three MMRTGs and secondary batteries to supply all electrical power during the mission.
- The electrical output of the three MMRTGs is ~330 We at BOM, corresponding to ~275 We at EOM (11 years after SRO launch).
- The power modes of the SRO spacecraft are divided into three distinct cruise-phase modes and three science-phase modes.
- The three cruise-phase modes are Launch, Cruise and Aerocapture & Circularize. The three science-phase modes are TCM (Hops and Translations), Science and Science and Telecommunications.
- The maximum power draw during the cruise phase modes is estimated at 293 We, driven primarily by the Cruise stage propulsion system used during the orbit circularization maneuver.
- The peak power draw of this mode exceeds the available RPS power, and thus redundant 400 W-hr batteries would be used to carry the peak energy demand of the ~2 hour circularization burn and subsequent clean-up activities.
- Batteries are the preferred solution rather than additional RPSs, as the circularization burn is a one-time occurrence and adding batteries is lighter (8 kg) than adding an additional MMRTG (45 kg).
- During the three science phase modes (TCM, Science, and Science and Telecom), the dominant power mode is TCM, with a power draw of ~287 We.

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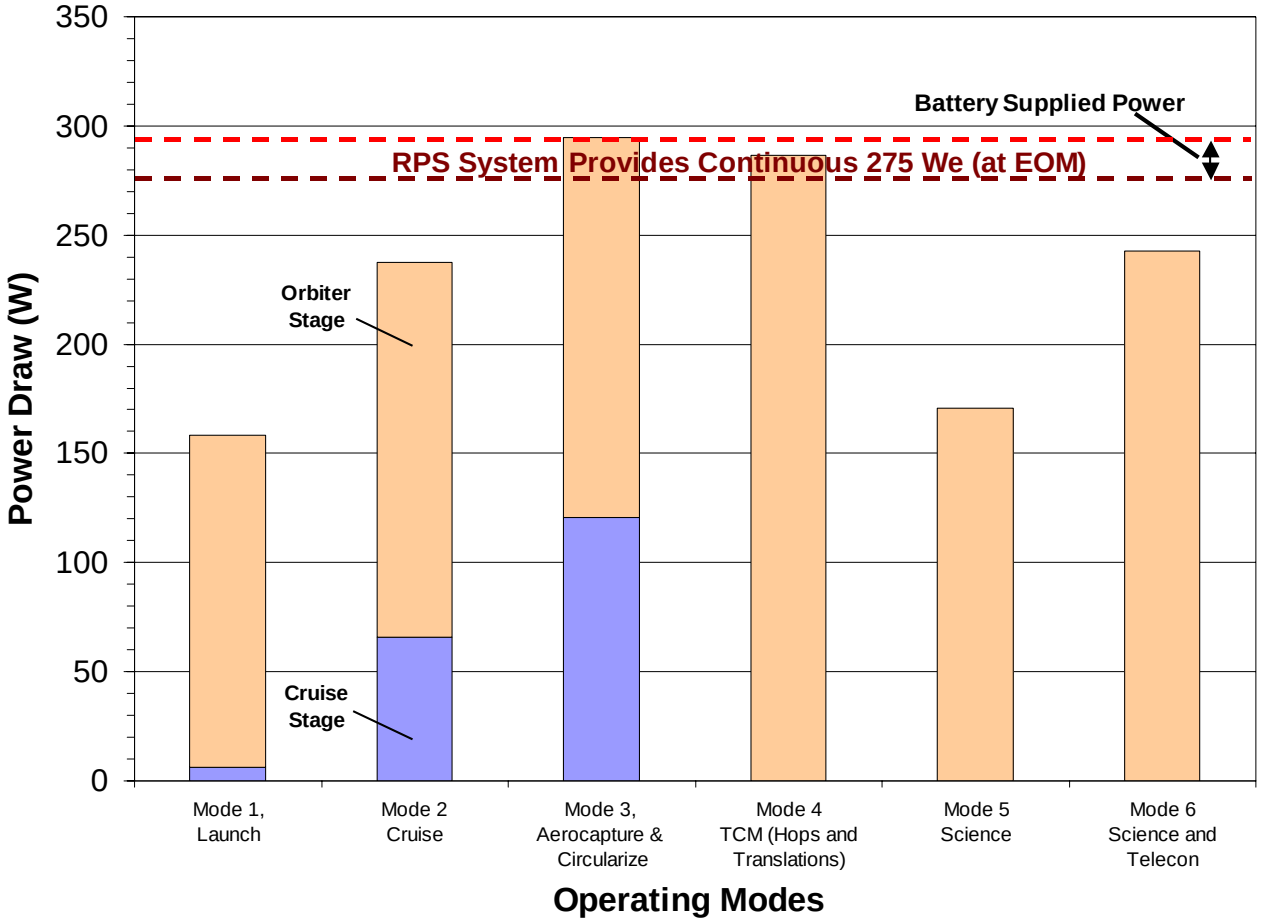
Power (2 of 2)

- This is driven by the operation of the propulsion system valves and the need to keep all instruments fully powered during the science mission in order to maintain their operating temperatures and keep them in a hot-standby configuration.
- Secondary batteries are used to cover the peak power demand during the TCM mode as it exceeds the steady state power output of the RPSs.



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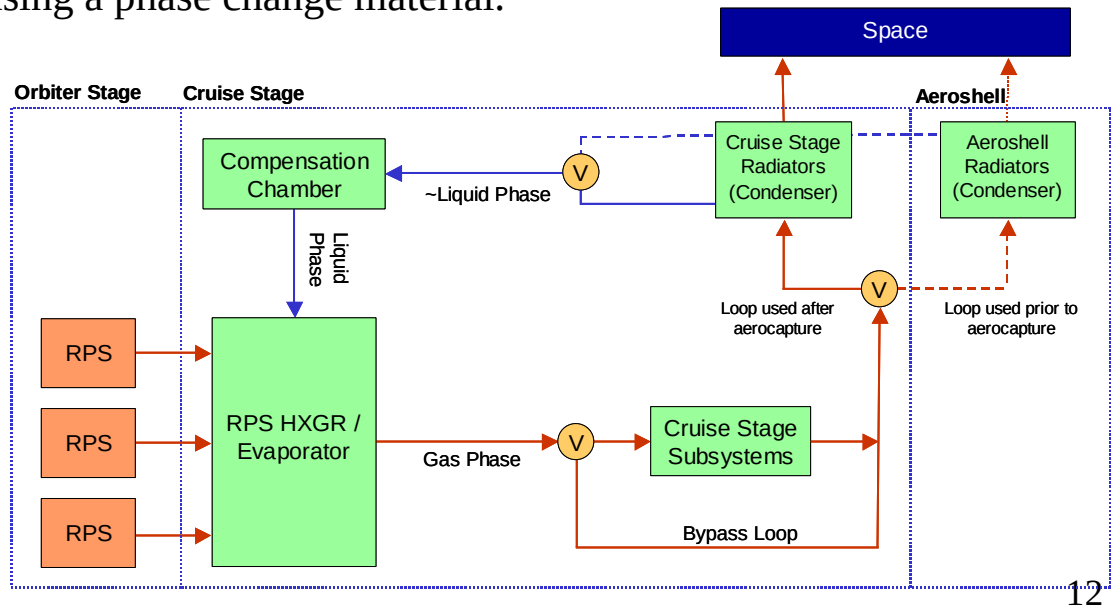
Thermal

- During cruise, loop heat pipes would circulate RPS heat through the Cruise stage to warm the propellant tanks. The RPS heat would then be rejected to deep space by radiators mounted externally to the aeroshell.
- The radiators would use thermal control louvers or polychromatic surfaces to actively control the heat rejection rate, and would be jettisoned just prior to the aerocapture maneuver to prevent them from being uncontrollably burned off during aerocapture.
- During the aerocapture event, the aeroshell would protect the Cruise and Orbiter stages from the intense external heat generated during their deceleration through Saturn's upper atmosphere via ablation.
- The heat generated by the RPSs during aerocapture would either be stored in the thermal mass of the system until aeroshell separation, or if determined to be too great (via detailed analysis), could be managed using a phase change material.
- Upon completing aerocapture and the subsequent circularization burn, the spent Cruise stage would be jettisoned
- This would expose the MMRTGs to the ambient space where their integrated fins would passively maintain their operating temperatures.



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Telecom

- The Orbiter would possess a gimbaled 2-m Ka/X-band HGA and a fixed Ka/X-band MGA.
- The HGA is the primary Orbiter antenna and would nominally be used for downloading science and engineering data in Ka-band during the science mission.
- The maximum HGA downlink date rate is estimated at 80 kbits/s, providing significant margin over the required data rate.
- This study assumes that the DSN's 34-m dish would nominally be used to receive all science and engineering data from the spacecraft and used for command uplinks.
- Were the DSN 70-m antennas used in place of the 34-m antennas, the data rates specified herein could potentially be increased by a factor of four.

SRO Stage and Antenna Type	Ka-band Data Rate 35 W (RF) at 10.5 AU	X-Band Data Rate 19 W (RF) at 10.5 AU	Description
Cruise Stage			
HGA (0.5-m) Ka/X-Band	5 kbits/s	167 bits/s	HGA is primary antenna for transmitting engineering data to Earth and receiving commands (both in X-band) during Cruise phase. Assumes 34-m DSN antenna. Ka-band also available as needed.
LGA X-Band Only	N/A	< 1 bit/s	X-band LGAs Used for near-Earth contingency purposes and spacecraft tracking during orbit circularization burn.
Orbiter Stage			
HGA (2-m) Ka/X-band	80 kbits/s	2.7 kbits/s	HGA is primary antenna for transmitting science and engineering data to Earth (Ka-band), and receiving commands (X-band).
MGA (0.1-m) Ka/X-band	200 bits/s	6.7 bits/s	MGA is backup to 2-m HGA and would be used for contingency purposes.

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Propulsion

- The Prop stage would use four gimbaled 890-N bi-prop main engines for DSMs and orbit circularization at Saturn, and twelve 0.7-N mono-prop thrusters for attitude control.
- The Orbiter would use four 45-N bi-prop main engines for ring hops, four 4.5-N and twelve 0.7-N mono-prop thrusters for roll control, RW desats, small TCMs, and attitude control.
- The Prop stage ΔV requirement is ~3650 m/s, with 3400 m/s allocated to post-aerocapture cleanup and subsequent periapse raise.
- The Orbiter stage ΔV requirement is ~2280 m/s, with ring translations requiring ~1510 m/s and ring hops requiring ~770 m/s.
- Four ring hops would be performed per orbit, corresponding to one hop every 2.5 to 3.25 hrs.
  - Each hop would impart an average ΔV of ~0.3 m/s.

Activity	Delta V (m/s)	Description
Orbiter Stage	**3650**	
Cruise Phase in Deep Space	250	Trajectory correction maneuvers and attitude control over 10 year cruise phase.
Periapse Raise	2900	Used to insert SRO into a circular 110,000 km orbit around Saturn following aerocapture.
Circularization Burn	500	Delta V required for orbital insertion cleanup maneuvers following circularization burn.
Orbiter Stage	**2275**	
Ring Hops	768	Average of 4 ring hops per orbit for 1 year. Corresponds to a mean delta V of ~0.3 m/s per hop.
Ring Translations	1507	Average of 1 ring translation of 3 km every week. Corresponds to a mean delta V of ~30 m/s per translation.
Total Delta V	**5925**	

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Mass Estimate

- The total wet mass of the SRO spacecraft, is ~21,000 kg including 30% contingency
  - Includes Orbiter, Propulsion stage, and aeroshell.
- The bulk of the SRO is comprised of propellant (~10,360 kg) and the aeroshell (~7740 kg).
  - Together, they comprise 86% of the launch mass.
- The SRO instrument mass would be ~130 kg, less than 1% of the total launch mass.
- The Orbiter's total mass is ~1820 kg (wet) including nearly 1,000 kg of propellant used for ring hops and translations.
- The Prop stage mass is ~11,450 kg (wet), including ~9380 kg of propellant used mostly for post-aerocapture cleanup and periapse raise.
  - ΔV~3400 m/s.
- The aeroshell mass is 40% of the approach mass (Hall, JPL) and estimated at ~7740 kg.
- Though the mass of the aeroshell appears relatively high, it is far lower than other credible near-term orbit insertion alternatives including the use of chemical rockets engines.

System or Subsystem	Mass w/ Contingency, kg
Orbiter Stage (Dry)	**842**
Orbiter Stage (Wet)	**1823**
Instruments	129
Subsystems	714
Propellant and Pressurant	981
Propulsion Stage (Dry)	**2070**
Propulsion Stage (Wet)	**11447**
Subsystems	2070
Propellant and Pressurant	9377
Approach Mass w/o aeroshell	**11607**
Aeroshell (40% of Approach Mass including aeroshell)	**7738**
Total Launch Mass (Dry)	**10649**
Total Launch Mass (Wet)	**21007**

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Summary and Conclusions

- Saturn's ring system is one of the most enigmatic objects in the solar system.
- To better understand the complex ring structure of this planet, the SRO would spend 1-yr in close proximity to Saturn's A and B rings to perform detailed observations and measurements of the ring particles and electric and magnetic fields.
- The SRO Orbiter would co-orbit 1 to 1.4 km from the ring plane, providing an unprecedented vantage point for making ring particle observations.
  - This data is would be used to enhance our understanding of the mechanisms of formation and evolution of planetary ring systems and protoplanetary disks.
- Due to the low solar insolation at Saturn and stringent spacecraft stability requirements, RPS is the only viable power system option for this mission.
- The reference mission baselined three MMRTGs to provide 275 We (EOM) to power to the spacecraft, augmented by lithium-ion batteries for load leveling.
- Alternately, four SRGs could be used - potentially with a mass savings due to their higher efficiency and lower heat output (requiring less phase change material).
- A natural follow-on to the Cassini-Huygens mission, SRO would be a challenging mission of significant scientific value.

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Questions
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