THE ICY MOONS OF SATURN: WHAT WE KNOW AND WHAT WE DON'T KNOW AFTER *CASSINI*:

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Introduction: During the last year of *Cassini's* life, valuable data was obtained and further analyses were done that answered many of the key outstanding questions on the icy moons of Saturn. A global ocean was established for Enceladuds (1), and good evidence now exists for a subsurface ocean on Dione (2,3) and Mimas as well. More accurate measurements of the heat production from activity on Enceladus were made (4). "Five Fabulous Flybys" of the inner ring moons of Saturn were successfully accomplished during the Ring-grazing Orbits, to reveal unique geologic worlds with histories that are intimately tied to Saturn's rings. Nevertheless, key questions remain on the composition, interiors, and specific surface features of these moons.

Enceladus: Questions on the heat budget of Enceladus, the specific mechanisms for creating this heat, and its variability persisted throughout the mission. Because the end of mission captured the south polar terrain of Enceladus in darkness, background heat produced outside of the tiger stripes could be more accurately measured. Seasonal changes were also sought at the end of mission, especially in the plume intensity. A special focus was put on gathering plume observations at a variety of mean anomalies, with the Imaging Subsytem (ISS), the Visible Infrared Mapping Spectrometer (VIMS), the Ultraviolet Imaging Spectrometer (UVIS), and the Composite Infrared Spectrometer (CIRS) taking simultaneous data. One of the last plume images is shown in Figure 1.

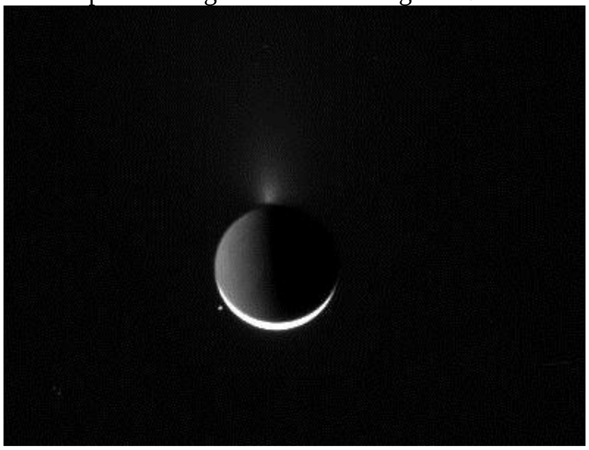

Figure 1. One of the last plume images obtained by *Cassini* on August 28, 2017. From JPL's raw image archive. https://saturn.jpl.nasa.gov/galleries/raw-images

Tethys: Although there were hints of activity on Tethys early in the mission (5), perhaps the most intriguing and outstanding puzzle for this moon were the "red streaks" that seem to be painted on its surface (6), and which are shown in Figure 2. The streaks do not appear to be associated with any tectonic features. A campaign was launched during the last two years of the mission to get better views of these streaks and to understand their global distribution. There is some evidence for compositional distinctiveness of the streaks, with enrichment in organic material, although grain particle size could also play a role (7).

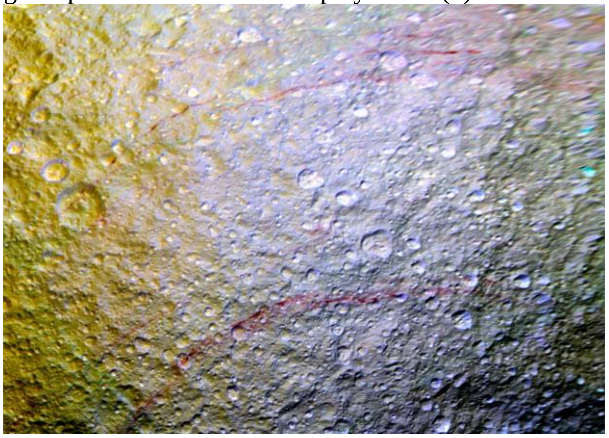

Figure 2. The mysterious red streaks on Tethys, which are not associated with tectonic features and seem to be painted on the surfact. NASA PIA 19637.

Iapetus: The observations during the end of the mission were focused on obtaining additional solar phase angles. Progress was made on understanding why there are so many large impact basins on Iapetus (8). One main outstanding question is the origin of its unique equatorial ridge; the idea of the accretion of a ring still stands as a viable idea (9). Evidence for a similar feature around Rhea is seen in the "blue pearls" painted on its surface. Ring systems may be common for small bodies in the Solar System.

Dione: Several lines of evidence point to past or even ongoing activity on Dione (10). During the last phase of the mission, special effort was given to large solar phase angle observations (see Figure 3) to search for forward scattered light from plumes or a transient atmosphere. As for the Enceladus plume observations, ISS, VIMS, CIRS and UVIS were all observing simultaneiously. So far, nothing has been detected, but further inspection of VIMS images at wavelengths where a previous transient atmosphere was detected remain to be inspected. Fields and part particle data also need to be scrutinized for particle loading.

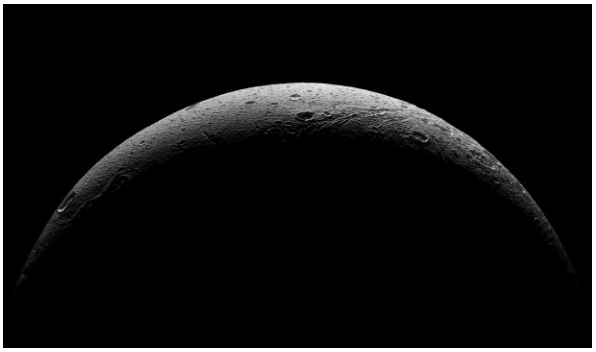

Figure 3. High solar phase angle images of Dione were obtained for plume searches; emphasis was placed on their acquisition in the mission's last year. So far, inspection of images has turned up nothing.

Ring Moons: "Five Fabulous Flybys" representing the "best ever" observations of five ring moons – plus a second bonus flyby of Epimetheus - dominated icy moon observations during the Ring-grazing Orbits. The Table summarizes these flybys and quantifies their improvement factors.

Table – the Six Ring Moon Flybys

Moon	Flyby Date	Close Approach (km)	Improvement
Pandora	12/18/16	20,000	~3
Daphnis	01/16/17	17,600	>10
Epimetheus	01/30/17	5900	6
Epimetheus	02/21/17	10,500	~3
Pan	03/03/17	23,500	2
Atlas	04/12/17	13,170	2

These observations led to "first ever" spectra for Pan and Daphnis, showing that the moons embedded in the rings accrete material containing a red chromophore originating in the rings. Complex geologic features and exotic "skirts" of material around the equators of some of the moons were imaged. The very low densities of these moons imply they are "rubble piles" that consist of reaccreted material.

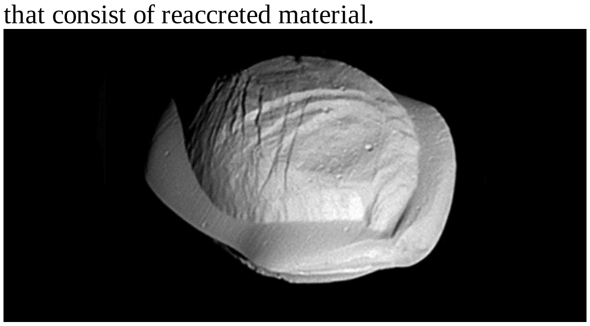

Figure 4. An image of Pan, which is embedded in the Encke gap, obtained on March 3, 2017. Accretion of ring particles forms a "skirt" around the moon. NASA PIA 21436.

Composition of the moons: Some of the remaining key questions on the moons relate to their composition, especially minor components. Organic material, including possibly polycyclic aromatic hyrodcarbons (PAHS) were identified on Hyperion and Iapetus (11,12), but some more specific hydrocarbons are difficult to identify because laboratory data is lacking. Another red chromophore that has been proposed for both surfaces and rings is nano-iron (13). The remaining questions on composition include:

1. Is ammonia hydrate found on the surfaces of any of the moons; tentative detections were made by Earth-based telescopes (14,15)
2. Can the D/H ratio be measured on any of the moons? This key question will be a thrust of future research for the main moons.
3. What are the tradeoffs between the various exogenic processes, including alteration by magnetospheric particles, or contamination by the red chromophore and E-ring ice particles?

The small outer irregular moons: Also during the final months of the mission, effort was put into getting observations of the outer moons in order to understand their dynamical states and interrelationships. These moons are difficult to observe from Earth, and the viewing geometrics attainabled by the Cassini spacecraft are not possible with ground-based telescopes.

Summary: Perhaps one of the most significant findings of the mission is the stark difference between the moons of Jupiter and Saturn. Jupiter's main moon system represents an orderly sequence that is a smaller version of the Solar System itself, while the saturnian system is dominated by stochastic processes such as collisional events. Many of the main moons of Saturn appear to be out of hydrostatic equilibrium, which would imply only partial differentiation and perhaps subsequent large collisions.

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