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Saturn's Rings after Cassini

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Introduction

Questions about the spectacular rings of Saturn have intrigued observers since the ring system was first glimpsed by Galileo in 1610. How did they form? What determines their structure? How are they held in place?

Although Jupiter, Uranus and Neptune also have ring systems, none is as spectacular as that of Saturn.

Among the many achievements of James Clerk Maxwell was his winning essay for the Adams Prize of 1856. In his essay, *"On the Stability of the Motion of Saturn's Rings"*, he showed that the rings had to consist, for stability and for observational reasons, of individual particles rather than exist in a fluid or gaseous form. Maxwell also investigated mechanisms by which a ring of particles could be stable under the long-term effects of mutual gravitational perturbations – an issue that is as relevant today as it was in the 19th century.

Summing up the feelings of many astronomers, Maxwell, in his essay, wrote: *"When we have actually seen that great arch swung over the equator of the planet without any visible connexion, we cannot bring our minds to rest… We must either explain its motion on the principles of mechanics or admit that, in the Saturnian realms, there can be motion regulated by laws which we are unable to explain."* [1]

Mainly as a consequence of recent results from spacecraft, we are fortunately now in a position to answer many of the problems posed by Saturn's rings without having to invoke any "*…laws which we are unable to explain*".

Early spacecraft observations

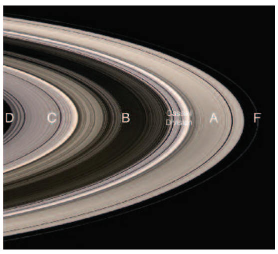

Image 1: *An annotated Cassini colour image of the main icy rings.The B ring appears rather dark, in this viewing geometry.*

Prior to the arrival of Cassini in 2004, three NASA spacecraft had flown past Saturn: Pioneer 11, Voyager 1 and Voyager 2 in 1979, 1980 and 1981 respectively.

Their initial views of the planet showed that the broad rings visible from Earth (named, in order of increasing distance from the planet, the D, C, B and A rings – see Image 1) appeared to consist of multiple rings.

The high resolution images sent back by the two Voyager probes showed that the F ring, first glimpsed by the Pioneer 11 spacecraft and located beyond the A ring, had a bizarre, braided appearance.

The images also revealed many of the, apparently separate, rings in the A ring were actually in the form of tightly-wound spiral waves, each caused by a gravitational resonance between the (orbital) period of ring particles at that distance and the (orbital) period of several small moons orbiting just beyond the main ring system.

Of course, what was really needed, instead of the brief glimpses of the rings from flyby missions, was a spacecraft which could orbit the planet for several years and make detailed studies of the rings' structure and composition. Such a spacecraft could monitor the rings and show how they evolved on a variety of timescales.

Cassini-Huygens

The Cassini-Huygens mission was a joint, international effort between NASA, ESA and ASI (the American, European and Italian space agencies, respectively). Launched in 1997, one of its goals was to deliver ESA's Huygens probe to Saturn's planet-sized moon, Titan.

After this, the plan was for NASA's Cassini spacecraft to continue to orbit the planet for at least four years. In fact, Cassini orbited Saturn for more than thirteen years, before it ran out of fuel and was deliberately targeted to burn up[2] in the planet's atmosphere in September 2017.

With a suite of twelve instruments on board, Cassini was the first spacecraft able to carry out a detailed, *in situ*, study of the Saturn system. More importantly, because the spacecraft was in orbit about the planet, it could monitor subtle changes in the system as well as respond to any new discoveries.

Ring properties

Although the main rings extend to a radial distance of 137,000 km, Cassini has discovered that their typical thickness is only about 10 metres, several orders of magnitude lower than previous estimates. Effectively, the rings consist of a monolayer of particles except at specific locations where additional factors, such as gravitational resonances and forced bunching of particles, operate.

All the individual particles are in orbit around Saturn and therefore obey Kepler's Third Law which implies that the disk has to be differentially rotating[3] – ring speeds vary from 17 kilometres/second (at the outer edge of the A ring) to twice as fast much closer to Saturn (in the D ring).

1 see the article by Andrew Whitaker http://www.clerkmaxwellfoundation.org/Newsletter_2015_Spring.pdf for an excellent discussion of Maxwell's essay.
2 in order to avoid any possible contamination of the moons, especially ones capable of harbouring life.
3 the speed of the particle orbits is proportional to the inverse of the square root of the distance from the centre of Saturn.

→

However, because the orbits of the ring particles are near-circular, the collisional speed between typical adjacent particles is only a few millimetres/second. Consequently, in the terminology of astrophysical disks, Saturn's rings would be described as a *"cold disk"* compared with a *"hot disk"*, out of which the planets are thought to have formed. Nevertheless, as we shall see, there are distinct parallels between the two types of disk which is why Cassini has given us insights into the processes of planetary formation despite the vast difference in scale (i.e. size).

We knew before, from ground-based observations of the reflectance spectra of the main rings, that they had to be composed primarily of water ice.

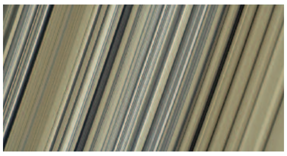

Image 2: *A natural colour Cassini image of part of the B ring. The image covers a radial range of 4,300 km and the resolution is 3 km/pixel.*

In fact, Cassini has determined that the rings are composed of 90–95% ice but with some additional impurities which may provide clues to their age. Although the rings evolved through mutual collisions, the distribution of particle sizes is not uniform with most of the mass being contained in the optically thicker, opaque B ring (Image 2).

The material in the optically thin C ring is remarkably similar to that in the Cassini Division separating the B ring from the A ring while the innermost D ring is very diffuse. There are also subtle compositional differences between the rings, perhaps indicative of a different origin.

Ring structure

Although the dominant force experienced by every ring particle is the gravitational field of Saturn, there are several additional perturbations.

One is the self-gravity between the ring particles themselves. This causes temporary, filament-like structures, perhaps 100 metres long and 10 metres wide, to form continually and then dissipate. Although these self-gravity *'wakes'* have never been imaged directly by Cassini's cameras (their size is just below resolution limit – 200 metres/pixel – of the best images) their existence has been inferred from a detailed analysis of stellar occultation[5] data acquired by Cassini.

As well as internal forces, the ring particles experience gravitational perturbations from a plethora of (mostly) small moons (mean radius typically less 100 kms) such as Atlas, Prometheus, Pandora, Janus and Epimetheus, orbiting just beyond the main rings.

The perturbing effect is particularly important at resonant locations where there is a simple numerical relationship (of the form $p+1: p$, where p is an integer) between the orbital period of the moon and the orbital period of the corresponding ring particle.

One very obvious example of such resonances is between the particles at the outer edge of the B ring (i.e. the inner edge of the Cassini Division) and the larger moon, Mimas (mean radius 198 km) i.e. a 2:1 resonance where p=1.

Kepler's Third Law essentially determines where such resonances are located and that is why it is the small moons orbiting close to the rings that have their resonances in the A ring.

The perturbing effect of a moon is amplified at the resonance, distorting the gravitational potential in a regular fashion. This in turn is felt by the surrounding particles and the net result is the creation of tightly-wound, spiral density waves at the resonance. If the perturbing moon is in an orbit inclined to the plane of the rings, then spiral bending waves result. These spiral waves permeate the A ring giving rise to characteristic patterns studied in detail by the remote sensing instruments on Cassini.

The resulting analysis has allowed the calculation of properties such as the surface density of the rings. The particles forming the edge of the main rings are located close to a 7:6 resonance (p=6) between these particles and the moon Janus. As a result, the A ring edge is *"scalloped"* in a way that bears a striking resemblance to some of the diagrams in Maxwell's original essay.

Ring gaps

The detailed images and occultation[6] data obtained by Cassini have shown that the rings contain several gaps.

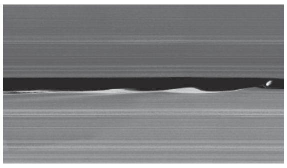

Image 3: *The 35 km-wide 'Keeler Gap' in the A ring along with the moon Daphnis. The well-defined wave on the outer (lower) edge of the gap has been produced by ring particles that have passed the moon and were perturbed.*

Two of these gaps, the 300 km-wide *'Encke Gap'* and the 40 km-wide *'Keeler Gap'* (Image 3) are located in the A ring and each has an embedded moon within it.

Each gap has almost certainly been created by its embedded moon (Pan in the case of the *'Encke Gap'* and Daphnis in the case of the *'Keeler Gap'*) as its presence scatters particles in the immediate vicinity.

Furthermore, as ring particles catch it up on the inside and pass by it on the outside, characteristic edge waves appear before being damped by collisions.

Cassini observations suggest that the gravitational effect of the embedded moon is to trigger the formation of moonlet clumps on either edge of the gap.

This gives some insight into what happens after planets have (1) formed in a protoplanetary disk, (2) have created a gap for themselves and (3) then interacted with the surrounding disk. In this way Cassini is giving us insights into how planets form.

Despite extensive searches with Cassini's cameras, we now know that not all gaps contain moons. Instead, many gaps contain isolated, narrow rings and there is speculation that the ring itself may act to create the gap.

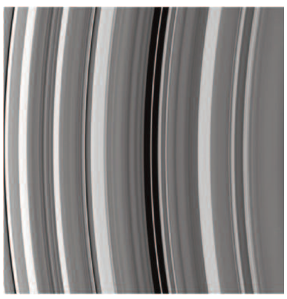

Image 4: *The central dark band in this Cassini image is the 270 km-wide 'Maxwell Gap' in the C ring. The image resolution is 5 km/pixel. Somewhat paradoxically, the 'gap' contains a narrow, sharp-edged, eccentric ringlet – the 'Maxwell ringlet'.*

Perhaps the classic example of a narrow, eccentric ringlet embedded in a sharp-edged gap is, appropriately enough, in the *'Maxwell Gap'* (and the associated *'Maxwell Ringlet'*) (Image 4) in the C ring at a radial distance of 87,500 km.

A detailed study of the ringlet using occultation[7] data has revealed a variety of waves, probably created spontaneously, travelling across the ringlet being reflected off each sharp edge. This and other gaps are still the subject of active investigation.

5 the concealment of stars due to the presence of these *'wakes'* obscuring the view.
6 See note 5.
7 See note 5.

Propellors

Saturn's rings are a system evolved out of collisions and with a characteristic size distribution of ring particles. While there are objects as big as Pan (mean radius 14 km) and Daphnis (mean radius 4 km), there are many more smaller objects, right down to dust particles.

Therefore, even although a 100 metre sized object in the rings is not capable of clearing a gap for itself (and cannot be resolved in Cassini images), it can still perturb nearby particles and it is this effect that can be detected.

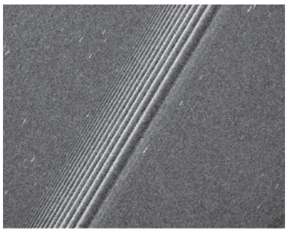

Image 5: *The characteristic pattern of a spiral density wave in the A ring. The small, bright streaks on either side are examples of "propellors". These are formed when an object too small to clear a gap for itself still produces its gravitational signature on ring particles nearby. The resolution is 385 metres/pixel, one of the highest ever obtained by Cassini.*

These are the so-called *"propellors"* (Image 5) discovered in distinct bands in Cassini images of the A ring. Their existence was first predicted on the basis of computer simulations of ring particles interacting with an embedded object. In images, their appearance is similar to that of a two-bladed propeller with a dark area in the centre where the *'perturber'* is located. They have been named (unofficially) after the pioneers of aviation.

Many hundred *"propellors"* have now been detected in the A ring and their positions tracked over time. Detailed analysis of one of the largest *"propellors"*, Blériot, has shown that its orbit is evolving with time, sometimes moving outwards and sometimes inwards in a stochastic manner.

This migration is probably the result of gravitational buffeting from some of the larger ring particles it encounters and it mimics the type of evolution we expect newly-formed protoplanets to undergo as they interact with the remnant disk out of which they formed.

This is another example of how Cassini is helping us to learn more about the dynamical process that operated in the early solar system.

The F ring and the Roche Division

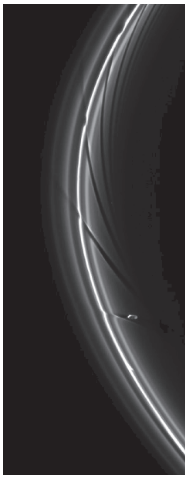

Image 6: *A Cassini image of Saturn's F ring and the structure imposed on it by the gravitational effect of the nearby moon Prometheus (86 km across). Each channel in the ring has been produced by direct perturbations from Prometheus as it approaches to and recedes from the F ring.*

The narrow, multi-stranded F ring at 140,000 km, with its perturbing moons Prometheus and Pandora on either side, displays bizarre, ever-changing structures. It is separated from the edge of the A ring by the *'Roche Division'* which contains the moon Atlas and a sheet of fine dust. This whole region is dynamically interesting because it is located close to where there should be a balance between tidal forces tending to break up a small moon and self-gravity tending to keep it intact.

Cassini images have shown a variety of small, probably short-lived, objects orbiting near to the F ring. By studying what happens as Prometheus passes the F ring (they move at different speeds around Saturn) we now know that each encounter can trigger the formation of new objects in the F ring's core (Image 6), much like what happens at the edges of the *'Encke Gap'*.

If these objects can survive the next encounter with Prometheus, they can grow and their orbits evolve, only to impact the F ring to produce jets of dust providing more material from which other objects can form. This intriguing, continuous assembly and disassembly of objects has been documented in Cassini images over the thirteen-year duration of the mission.

Origin and Age of the Rings

Given the high ice content of the rings, it is natural to consider that a giant passing comet (tidally disrupted by Saturn) could be the origin of the rings. However, this will only work if such comets arrive from the Oort cloud sufficiently frequently and are disrupted in just the right way; current thinking suggests that this is unlikely.

An alternative theory proposes that the rings originated from the disruption of a Titan-sized moon as it spiralled into the planet under the dissipative effects of tides. The moon could have had a rocky core, and an icy mantle, with the disruption causing the core to be absorbed by Saturn while the mantle was left to form the ring system.

Linked to the origin problem, is the question of the age of the rings and their mass – the more massive the ring, the older it should be because of processes such as viscous spreading.

Furthermore, the mechanism whereby orbiting moons can generate spiral waves in the main rings at resonant locations (see above) has consequences. There should be an exchange of angular momentum between ring particles and moons meaning that, over time, the rings should be collapsing and the moons' orbits expanding.

The Voyager values of the surface density of the A ring led to the first estimates of the rate at which this was happening. This suggested that the rings were perhaps only 400 million years old, an uncomfortably small fraction of the age of the solar system, with a mass perhaps 75% that of Saturn's moon Mimas and their remaining lifetime may be their current age.

Cassini undertook several experiments designed to refine these estimates. During the final stages of the mission, radio tracking was used to obtain a measurement of the mass of the rings. This suggested that a mass of only 40% that of Mimas was more likely, with a calculated age between 10 and 100 million years.

A different approach was undertaken by Cassini's dust analyser. The goal was to determine the physical nature and flux of material coming into the Saturn system from outside. The main source of infalling material was shown to be the *'Kuiper Belt'* and, when this material impacted the rings, it would *"pollute"* the pure ice at a, presumably, constant rate. Therefore, by measuring the degree to which the rings were polluted, an estimate of the age of the rings could be obtained.

This suggested a ring age of between 100 and 200 million years. The consensus appears to be that the rings are indeed considerably younger than Saturn itself and therefore they are not primordial.

Maxwell's Legacy

Maxwell's Adams Prize essay was a triumph of mathematical physics with its remarkably prescient analysis of a difficult problem although Maxwell himself realised that his model of the rings was idealised.

He would have appreciated the enormous progress that has been made in understanding and explaining the true nature and complexity of the rings as revealed in the images and data sent back from Cassini.

That *"great arch swung over the equator of the planet"* still has its mysteries – it was Maxwell who first showed us the way forward.

Images courtesy of NASA/JPL-Caltech/Space Science Institute.

Visit to Einstein's House

by **David Forfar, MA, FFA, FIMA, FRSE, Trustee of the James Clerk Maxwell Foundation**

Figure 1: Einstein's summer house. *Courtesy : Einstein Forum*

Figure 2: The view from Einstein's House towards the Templinersee where Einstein sailed. *Courtesy : James Clerk Maxwell Foundation.*

Introduction

In June 2018, I (as the immediate past chairman of the Maxwell Foundation) had the privilege of a tour of Einstein's summer house in Caputh, some twenty miles from Berlin. It was built for Einstein and was the only house that Einstein ever owned. The house was built in 1929 and Einstein left the house, in 1933, when he left Germany for good. During the period when he lived there, Einstein was Professor of Physics at the Kaiser Wilhelm Institute in Berlin.

The plan of Konrad Wachsmann

The story[1] of how the house came to be built for Einstein, by a certain Konrad Wachsmann, is rather interesting. Not only had Konrad Wachsmann never met Einstein but he hardly had the credentials to build a house for a world-renowned scientist who, by that time, had been awarded the Nobel Prize for Physics.[2]

Konrad Wachsmann was employed by the firm 'Christoph and Unmack' which specialised in the construction of wooden houses. Wachsmann had only read in the newspapers that, in order to celebrate Einstein's fiftieth birthday (in 1929), the City of Berlin wanted to build Einstein a house. Einstein had expressed a preference for a wooden house and this was enough the make Wachsmann determined that he was going to design a summer house for Einstein.

Wachsmann thought long and hard about how he might reach Einstein. He realised that it would require considerable initiative on his part. Undaunted, he devised a scheme.

The first visit to Einstein's house

He first looked in the Berlin telephone directory and, by that means, found Einstein's address. Next, he arranged for a chauffeur from the Berlin branch of his firm to be on stand-by to drive him to Einstein's apartment. Finally, he travelled by train, from the German city of Niesky where he lived, to Berlin; a distance of some 60 miles.

He impressed Mrs. Einstein through a combination of bluff (he said he was a freelance architect whose private chauffeur was waiting outside) and chutzpah (he said there was no other architect in Germany with more experience of wooden houses than he).

Mrs. Einstein told him that her husband was not at home but would be in, on the next day. Konrad Wachsmann, undaunted, said that he would return the next day to discuss the details with Professor Einstein personally.

On the way on the train back to Neisky, Wachsmann began work on a preliminary set of blueprints suitable for a wooden summer house.

He did not finish these until the very early morning of the next day. He then had a team of ten engineers and draftsmen from his firm transform his designs into a finished house plan. By the afternoon of that day, he was on the train back to Berlin with the finished plan.

The second visit to Einstein's house

After reaching Einstein's house for the second time, he was introduced to Professor Einstein himself and showed him the finished plans which contained the detailed blueprints, calculations and building specifications that had already been made for a wooden house. Einstein was a little suspicious as he doubted that he (Wachsmann) could have completed a finished plan in so short a time.

In order to gain Einstein's trust, Wachsmann revealed the truth, namely that he worked for a firm of house builders, he had stumbled across the (aforementioned) newspaper article, that he had been up all the night working on preliminary designs and that he had had ten engineers and draftsmen urgently transforming the designs into the finished plan.

The house is built

Einstein apparently then laughed; he said he could not but admire Wachsmann's initiative, boldness and keenness to obtain the work.

After the making of some alterations to conform to Einstein's wishes and after the purchase of suitable land in the village of Caputh (20 miles from Berlin), the design of the wooden house was finalised and the house was ready by September 1929.

The house is a substantial summer house. There is a large sitting room for entertaining guests, a study, a number of small bedrooms and a kitchen and large balcony.

The house made a welcome haven from the rather formal protocols of the Berlin Academy. Einstein could relax there. He liked to go for walks in the surrounding woods. There, Einstein could entertain, in a more informal manner, important guests such as Max Planck, Chaim Weizmann (later President of Israel) and other prominent people.

Only ten minutes from the house was a lake, the Templinersee, where Einstein could enjoy sailing his boat.

Einstein's tribute to James Clerk Maxwell

Einstein lived in the house (except for a few months in the winter) from 1929 to 1933 Germany and wrote several scientific papers in the house, including his famous tribute to James Clerk Maxwell which appears in the 1931 commemorative volume[3] celebrating, in 1931, the centenary of Maxwell's birth.

Einstein's farewell to the house

Einstein bid farewell to the house in 1933, when Hitler assumed power in Germany. He was leaving Germany, never to return.

1 For details see 'Einstein Forum, *'A Place of Passage: Albert Einstein's House in Caputh'*, Potsdam (2010).
2 Einstein received the 1921 Nobel Physics prize for his analysis of the photoelectric effect.
3 *James Clerk Maxwell, a Commerative Volume*, Essays by Sir J.J. Thomson, Max Planck, Albert Einstein etc. Cambridge University Press (1931).