Journal of Applied and Fundamental Sciences

DUSTY PLASMA IN SATURN'S RINGS: A LITERATURE REVIEW

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Abstract: The importance of dusty plasma physics for understanding the dynamics and characteristics of Saturn's rings was realized much before the in situ observations made by the spacecrafts such as the pioneers, voyagers and Cassini. However, it was the observation of radial 'spokes' by the Voyagers 1 and 2 above the Saturn's B and C rings that established the importance of dusty plasma physics in the study of Saturn's ring system. Since then dpp (dusty plasma physics) has been successfully used to explain several observations or phenomena of the Saturn rings. However, many questions remained unanswered. The questions with regard to the plasma sources, plasma transport or dynamics and the interactions of ring particles with the plasma in the presence of the planet's magnetic fields are yet to be fully understood. There is a hope that the complete analysis and interpretation of the numerous Cassini data will lead to a deeper understanding of the Saturn rings. Several papers on Saturn rings from Pioneer to Cassini are reviewed here. The objective is to present an up-to-date comprehensive paper on Saturn's rings by incorporating the findings of Pioneers, Voyagers and Cassini. The motivation is to identify the areas/ ideas/topics on which further research should be taken and the extent to which the dynamics and evolution of the Saturn ring system is governed by the dusty plasma physics.

Keywords: dusty plasma; Saturn rings; main ring; spokes; diffuse rings; F ring; Saturn magnetospheric plasma

1. Introduction:

The confirmation made by Voyagers 1 and 2 about the presence of micron and submicron size grains as 'spokes' and ringlets in the main ring, D rings and tenuous rings (E, F and G) indicated that gravitational forces alone would not be able to explain all the observations of the Saturn's ring system[1, 2]. For a system dominated by fine dusts (micro and sub-micron particles) non-gravitational forces (the physics of which is governed by dusty plasma physics, DPP) plays pivotal role in their dynamics and evolutions [3]. Dusty plasma physics have been successfully applied in understanding the interaction between dust particles, the plasma, and neutral molecules such as in comet and Jupiter rings. In the case of Saturn's rings the application of DPP is complicated by the Saturn's magnetic field which itself is not yet well understood. Since the magnetospheric plasma conditions are subject to random fluctuations the grain charge too fluctuates [4-10]. The answers to the questions as to origin and formation of the dusts are still speculative. Whether they are brought into or created within the Saturn rings is still an open question.

Nonetheless, we do have ample evidences obtained through observations and/or measurements of the dusty plasma at play in the Saturnian rings system. We believed that the complete analysis and interpretation of the numerous Cassini data will lead us to deeper understanding of the Saturn rings. The objective is to present an up-to-date comprehensive paper on Saturn's rings by incorporating the findings of Pioneers, Voyagers and Cassini. The motivation is to identify the areas/ ideas/topics on which further research should be taken and the extent to which the dynamics and evolution of the Saturn ring system is governed by the dusty plasma physics.
Since there are so many published papers on the topic we review only the papers or theories that have been well accepted. For the same reason the details of various theories and mathematics have been omitted. Only the core of the theories/models and their results and/or conclusions are given. Here, it must remember that the external plasma sources like the solar wind, though not discussed, too affect the dynamics of the Saturn ring. For instance, the distance between the magnetopause and the planets and the magneto disks can be altered by the solar wind pressure [6, 8].

2. Basics of DPP which is the theoretical background of the topic:

Dusty Plasma:

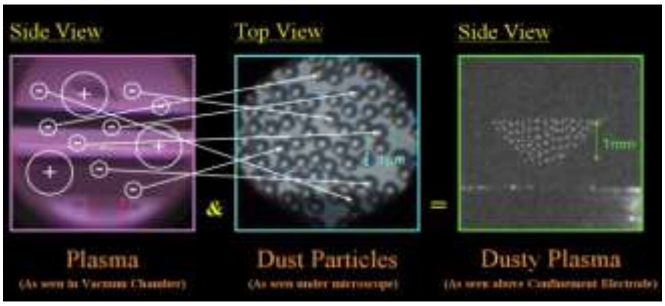

Figure 1: Complex Plasma (or Dusty Plasma) is compromised of dust particles submerged in plasma Courtesy ::http://www.physics.usyd.edu.au/app/complex/introduction.html 17 Jan 19, 10.06 a.m

Plasma is an ionized gas (a sea of ions and electrons). To simply put it Dusty plasma is a system consisting of ions, electrons, neutral atoms and charged micro particles. In a dusty plasma the inter grain spacing (d) should be between the grain size (a) and the Debye screening length (λ_D) so that the dust themselves is involved in the screening process and formed a collective ensemble. [9]

2.1. Charging of dust in a plasma:

In the cosmic environment dusts in a plasma can gain charge in different ways such as by:
(a) Collection or absorption of electrons and ions from the background plasma.
(b) Secondary emission or sputtering due to energetic electrons or ions impact.
(c) Impact ionisation/ vaporisation
"Impact ionisation occurs when a neutral atom or ion strikes a surface with sufficient kinetic energy that either the incident neutral or atoms on the surface are ionised with subsequent escape of ions and/or electrons." Whereas impact vaporisation occurs when "a small particle such as a dust grain vaporises and ionises into a cloud of plasma upon impacting a surface at high speed."[1]
(d) Photoelectron emission of the grains by UV radiation and Thermionic emission. The charge thus obtained by the dust can be either negative or positive charge depending on the surrounding plasma environments and the chagrin process. Secondary emission can cause the grain to become positive charge [1, 8 10-15].

2.2. Dust dynamics:

Once dusts acquire charges non-gravitational forces like electrostatics force, electromagnetic force, drag force (e.g. ion drag force) and radiative pressure started to influent their dynamics [15]. This results in variation of density and charge distribution of the plasma, modification of plasma wave propagation, instabilities or scattering [12]. Which in turn give rise to dust-acoustic wave (DAW) [13].

3. Overview of the Saturn rings:

The Saturn ring system is a "two-phase system of gaps and dense clumps" [16]. From the inner edge to the outside edge the Saturn rings are named E, G, F, A, B, C and D (Figure 2). The rings A, B and C are much more massive and more opaque and are known as the main rings. While the rings D, F, G and E are known as diffuse or tenuous or faint rings [16-21].

"The rings are dynamic and constantly evolving. Their compositions change on timescales of days, months and millions years"[21]. Since "photons, charged particles, and interplanetary meteoroids strike the rings" the ring particles are mainly aggregates of smaller elements that are temporal stuck together into elongated clumps. These temporal clumps can grow or get fragmented [16]. The balance between these two processes of accretion and fragmentation results in the distribution of particle sizes and velocities. [19, 21]

The ring particles are predominantly 99 % water ice in crystalline form [4,19]. This implies that the rings could have been the outcome of chemical reactions involving oxygen in the ring environment. This ice component parts make the rings bright while the non icy components (tholins, polycyclic aromatic hydrocarbons, or nanohematite) are believe to be responsible for the reddishness of the [16] .

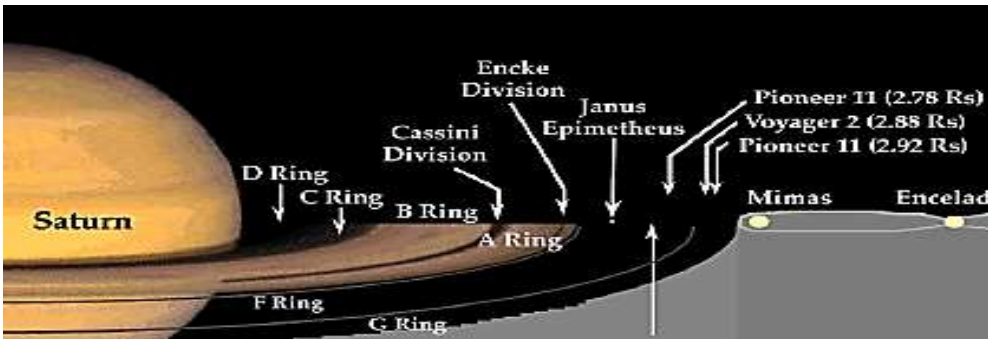

Figure 2: Saturn rings system image, courtesy : " Passage to the Ring World" pg. 46 of [19]

The main rings and the diffuse ring have different dynamics due to the difference in their particle sizes; the light particles are influenced by electromagnetic forces while a meter-sized particles by gravitational forces [18].

3.1. The main rings:

The main rings have different evolution and possibly different origins [21]. Water ice is the predominant constituent of these rings [20]. The size of the particles in these rings ranges from centimetres to meters sizes following a power-law distribution and are continuously colliding each other at speeds <1 cm/s every few hours. Due to their closeness to Saturn and relatively larger particle size the dynamics of the main rings are significantly influence by the planet tidal force. For instance, the tidal force prevents the particle to agglomerate into small moons [19, 25]. Near the Roche limit temporal agglomerations of ring particles might be formed [23] if the ring mass density is large enough. The main rings do not contain much dusts, except as "spokes" in Saturn's B rings [25] or in the narrow and diffuse regions of the Encke Gap ringlets and Laplace Gap .

3.2. Dusty Plasma in the Main rings:

3.2.1. "Spokes", the "localised charged dusts" in Saturn's main rings:

Saturn's spokes are 'cloud-like' levitated charged micron size or submicron size dusts [10, 26, 44] that were first observed above the Saturn's B ring by voyager I spacecraft in 1980. They are usually 'wedge-shaped', with the inner portions wider than the outer portions.[28].

The confirmation of the electrical nature of the spokes came from the edge-on observations of the ring system by Voyager 2 [30]. From the estimation using the Voyager 1 and Voyager 2 images the period of spokes was found to be 621 ± 22 min which is almost the same periodicity of Saturn's magnetic field, 639.4 min. The similarity implied that the spokes were charged particles. Also ,the spokes were found to be predominantly moving over time scales of order 30 min at Keplerian angular velocities rather than the angular velocity of the magnetic field.

From these findings it became clear that the spokes were charged particles drag around by Saturn's magnetic field [29 - 32]. However, the nature of charge/s of these particles is still elusive. Besides, the source(s) and the charging mechanism of the spokes are actively being debated.

From the nature of spokes it is obvious that that spokes in Saturn magnetospheric plasma under the influence of the Saturn's magnetic field constitute a system of magnetised dusty plasma physics. More recently additional spokes were also sighted by the Cassini in mid-2006. In the following discussion we will see that till today the mechanism of spokes formation, dynamics, characteristics and morphologies have never been fully understood.

3.2.2. Saturn's 'spokes': dynamical characteristics and morphology:

3.2.2.1. Particle size:

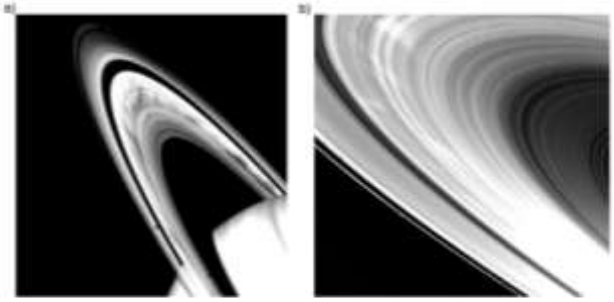

Figure 3: Images of spokes in the B ring (Smith el al, 1981) Courtesy: NASA/JPL-Caltech [27]. (a) Image captured in backscattered light (b) Image taken in forward scattered light.

The spokes appeared bright in the forward scattered light and dark in back scattered light (figure 3). Since this type of scattering is the characteristics of particle whose sizes are comparable to the wavelength of visible light it was concluded that Spokes are micron-sized particles levitated above the ring plane [26-30].

Estimation using keplerian velocities the lower limits of grain sizes was found to be of the order of 0.1 mm [33]. However, grains stability criteria against electrostatic and centrifugal disruption suggested the grains radii to be of the order of 0.5 – 3 mm. While Doyle and Grün (1990) estimated the grain size was 0.6 (± 0.2) µm which is consistent with sub-micron size spheres of pure water ice . This was supported by calculation of Colleen A. McGhee (2005) who found the effective spoke particle size to be of the order 0.6 µm. Also, the spectral analysis of spokes by D'Aversa et all, (2010) detected on the B rings on the on 9^{th} July 2008 by the Cassini found them to be consistent with a population of spheroidal water ice particles with a wide size distribution centered at about 1.90 µm. [36-38]

3.2.2.2. Location and Extend of the spokes:

The spokes seem to be appearing suddenly and more frequently near Saturn's equinoxes, in the morning ansa of the rings. They were not found near the synchronous orbital radius, where the Keplerian velocity of the ring particles equals the rotation velocity of the Saturn's magnetic field [38, 44]. Carolyn C. Proco et all, (1982, 1983) suggested that maximum spoke activity is most likely occurs within a range of magnetic longitudes containing the source region of the SKR (Saturn Kilometric Radiation) on the morning half of the rings. Passage of this region through Saturn's shadow may play a significant role in the creation and/or rejuvenation of spokes. The spoke activity (formation and growth in width) in the nightside hemisphere of Saturn is higher than that of the dayside hemisphere by a factor of 3. [30-42].The location of the spokes corresponds to the most optically thick region of the main rings. [2, 43]

3.2.2.3. Seasonality:

Spokes activity decreases with the sun altitude and entirely vanishes at tilt angles above 15°.. This was thought to be due to photometric effect. Based on this idea, Cassini was expected to observe activity as it enters the Saturn orbit in 2004. But Cassini did not find any spokes till September of 2005, over a year after orbit insertion [36]. This could be an indication that the formation of spokes is a seasonal phenomenon. According to Farrell et al. (2006) it could be that the formation mechanism had simply stopped or were much less active. Another possibility is that the formation of spokes is continuous, but the charging environment above the ring can under certain circumstances rapidly destroyed them. [41, 45]. It could also be that due to the seasonal effect in the occurrence of thunderstorms at a particular latitude the spokes were absence between 1998 and 2005--about one quarter of a Saturnian year.

The seasonal nature of the spokes and the dependence of its activity with the sun angle implied that solar illumination has effect on the density and charge of the plasma generated by photo dissociation due to solar UV photons and fluxes of magnetospheric particles. "The ability of charge dusts to levitate above the ring surface may be inversely depended on the photoelectron density in the ring ionosphere." If this is the case then spoke formation will be possible only when and where the solar flux incident on the rings is low (i.e. near equinox and in the Saturn' shadow.) [46-47]. Based on the above arguments spokes are expected to disappear as Saturn nears its northern hemisphere summer. No confirmation or proof has been established to this.

3.2.3. Theories of spokes formation:

3.2.3.1. Goertz and morfill model 1983 (GM Model):

The model proposed by Goertz and Morfill (1983) (a schematic view of the given in Figure 4) suggested that a meteoric impact on the rings created a radially expanding dense plasma (about $n_e = 10^{15}$ cm^3) cloud above the ring plane. This plasma cloud charged up the dust particles at the surface of larger particles of the rings. The electric fields of the charged dusts can become strong enough to overcome the gravitational force and may get themselves electrostatically lift them off the ring and moves with keplerian orbiatal speed. While the plasma column, which move with the speed of the meteorite eventually corotate with the Saturn's magnetic field when its density fall below a critical value (ne ' 10^2 cm^3). The relative speed between the two causes an azimuthal polarization electric field of the plasma making the spokes move radially forming a radial dust trail above the ring. After approximately half an orbital revolution the suspended particles settle back onto the ring.

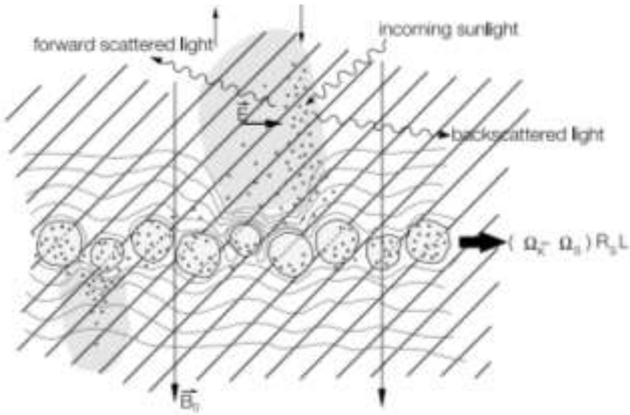

Figure 4: Underneath a dense plasma column (indicated by heavy shading) the equipotential contours are compressed and a large surface electric field exists. Dust particles are lifted off the rings and drift through the cloud, which polarizes. A pair of field-aligned currents closes the current. Courtesy:pg 214 of reference [33]

This theory was able to explain some of the characteristics of the spokes such as its formation, levitation off the ring plane and the radial alignment. But the meteoric bombardment of the ring that created the dense plasma clouds itself becomes a mystery. Besides, if meteoric bombardment did take place the transient plasma cloud would have to drift along the full radial extent of the spokes in minutes. Alison J. Farmer and Peter Goldreic (2005), found that the drift velocity cannot exceed the difference between the local keplerian and corotation velocities.). “The radial orientation of new spokes requires radial speeds that are at least an order of magnitude faster. The model advanced by Goertz and Morfill fails this test.” [35]. However, G.E Morfill and H.M Thomas defended the GM model by arguing that the plasma cloud model satisfies all available observational and physical constraints [39].

The GM model also did not say anything about the locations of the spokes formation, shapes, and periodicity of its activity as discussed above. Besides, it failed explain they have clustering behaviour and were not visible bewteen October 1998 and September 2005. Jones, G. H., et al. (2006) argued that meteoroid impacts cannot account for the observed sustained build-up along a spoke's central azimuth. “This would require an extremely unlikely sequence of recurring impacts at the same ring location.”[40].

On the other hand, the support for the above meteoric bombardment theory got support from various data collected by the Cassini. Some of these are:

1. Data from the Radio and Plasma Wave System (RPWS) provided evidence for meteoroid bombardment in high density regions of the inner Saturn magnetosphere.[36a]
2. Colleen A. Mc Ghee et al. (2005) found that the effective particle size was consistent with predictions of plasma cloud models[36]
3. Coates, A. J., et al. (2005) reported the observations of thermal (0.6–100eV) electrons near Saturn's main rings during Cassini's Saturn Orbit Insertion (SOI) on 1 July 2004 [26].
4. Matthew S. Tiscareno et all (2013) observed dusty clouds in Saturn's rings, that are formed possibly from impacts of a stream of Saturn-orbiting material derived from debris of a meteoroid (of radius 10 to 50 cm)

onto the rings. They suggested that such impacts could be a trigger mechanism for the “spokes” observed in the B ring. [48].

3.2.3.2. Thunderstorm model:

Jones, G. H., et al. (2006) proposed that spokes were caused by lightning-induced electron beams striking the rings, at locations magnetically connected to thunderstorm. They suggested that a terrestrial lightning discharge created a strong electric field above the associated thunderstorms. In the presence of this electric field an upward electron avalanche can take place above the thunderstorm when incoming cosmic rays cause the ionization of atmospheric particlesy. In case the atmospheric density is low enough, such electron avalanches can escape into the magnetosphere. The escaping electrons travelled along Saturn’s magnetic field lines and hit the rings thereby inducing negative charge on the grains. In the process the ring atmosphere also get ionized, dissociated, and excited. A small quantity the dust grains on the surface of the boulders that collected an extra electron gets repelled by the electrostatic forces. Eventually they get accelerated away from the ring dense transient plasma cloud and joined the permanent background plasma [41,44]

JONES ET AL.: LIGHTNING-INDUCED RING SPOKES AT SATURN

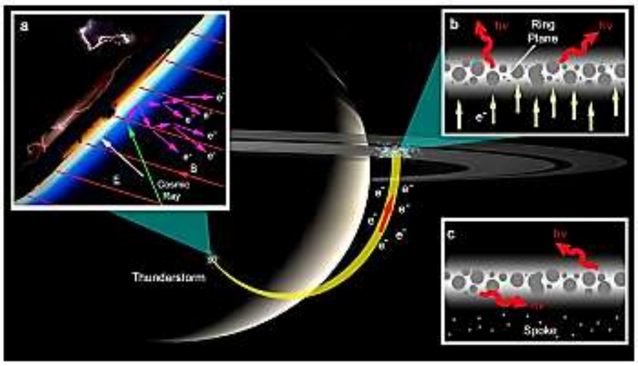

Figure 5: The spoke formation process: (a) electron avalanche (b) charging of ring grains (c) small grain regoliths are repulsed by the ring to form a spoke. Courtesy : pg.3 of [42]

Though the thunderstorm model explains several aspects of spokes’ morphologies like the clustering behaviour it doesn’t account for the narrowness of the spokes (Colin Mitchell). Besides, no thunderstorm has been observed so far [41,50].

3.2.3.3. Hill and Mendis model (1980):

Hill and Mendis (1981, 1982) proposed that field aligned currents flowing from the magnotail of Saturn generated double layers electric fields in the upper part of the planet’s ionosphere. This results in a potential drop across the double layers and caused the acceleration of electrons. These accelerated electrons moved into the field lines on the equatorial plane (on the night side) of the planet and charged up the large bodies in the main ring. Thus the dusts in the bodies too get charged. When the grains charge becomes large enough they are carried away by corotating field forming what we called “spokes”. These spokes keep rotating within the shadow region. Once they are out of the shawod region they are discharged by the solar radiation and thermal plasma and are brought to a potential corresponding the cooler thermal plasma. Once their potential become low they are now influenced by the gravitational field and thus move with the Keplerian speed and gradually dissipate. Eventually the grains returned to the ring plane.

Hill and Mendis (1981) invokes the interaction between the solar wind’s convective electric field and Saturn’s magnetospheric plasma to cause magnetic field-aligned drops in potential. This process, however, only operates at auroral regions magnetically-connected to Saturn’s magnetotail, whereas the main rings reside in a dipolar magnetic field region unconnected to the tail. Aslo, the underlying charging process must be one capable of occurring at the mid-latitudes to which the rings map, at a point co-rotating with the planet for >1 hour, and being most active in the morning sector. Neither of the two models above can meet all these conditions.

Unlike in the model of GM where the spoke evolved radially according to this model the spoke formation is instantaneous. However, Hill and Mendis (1981, 1982) model failed to explain the mechanism for the formation of the double layers (41-42).

From the above discussion on the nature of the spokes it is clear that the spokes phenomenon is related to charged dusts, electrons, electric field, magnetospheric plasma and magnetic field. This is to say that the understanding of the spokes phenomenon is in the realm of Dusty or Complex plasma.

3.3. Dusty plasma in the diffuse rings and F ring of Saturn:

The electron and the ion density measurements of the RPWS/Langmuir Probe (LP) instrument of Cassini in 2016 found significant ion/electron density in the faint rings of Saturn. “The relationship between the observed charge densities and the electrical potential of the grains shows that the grains and the ambient electrons and ions are electro dynamical ensemble, dusty plasma”. The characteristic of dust size appears to depend on the distance from the ring centre which means a dusty plasma state is related to the dynamics of the grain sizes [51]

3.3.1. Diffuse rings:

The rings D, E and G are known as the diffuse rings. These rings are in direct contact with the Saturn magnetospheric plasma which appears to determine their structure. Plasma disturbances in the plasma density and/or mean energy, by magnetospheric and solar wind processes can induce stochastic charge variations on the dust particles, which in turn can lead to an orbit perturbation and spatial diffusion. Besides, sputtering and Coulomb drag forces appear to be important parameters in determining the structures of the diffuse rings. Many of the observations on the dusts within these rings await theoretical explanations. [53]

3.3.2. The D ring:

The D ring is the innermost (closest) ring of Saturn. The ring has a normal equivalent width of 15m. It contains highly changeable and different particles populations of sizes between 1 to 100 microns. It has three major rings D68, D72 (typical particle size is roughly ∼10 microns) and D73 (mean particle size around 2 microns) and a set a ‘wave-like structures’ around them.

It is speculated that the mechanism for the particle motions in these ringlets involves inter-particle interactions. The region between D73 and the C ring is the most complex part of the D ring [4, 20-21, 48-49] . This D ring region contains resonances with the periodic Lorentz forces on charged grains Cassini made several new observations which are either newly formed or were not observed by Voyagers or had changed over the years. The peculiar observations of the D rings are (i) the structural changes over the time (about 25 years) between the Voyager and Cassini visits. (ii) The ringlet D73 had become more diffuse and wider by 210 km. (iii) The center of brightness of the D 73 had shifted inwards by over 200 km. (iv) Additional ringlets and structures in the D ring. (v) fine-scale structures that appeared to be variable in time and/or longitude. (vi) A regular, periodic structure with a wavelength of ∼30 km extending between orbital radii of 73,200 and 74,000 km.(vii) Radial movement of D68. [56] Most of the observations mentioned above still await explanation.

Another puzzling feature in the D ring is the longitudinal variation of the brightness and position of the D68. Headman et. all. (2006), suggested that the periodic structure could be due to a differential nodal regression of an initially inclined ring formed in response to an impact with a comet or meteoroid in early 1984. There are no nearby large object as dust source which usually is the case in other ringlets such as in the main rings. The absence of large object such as moonlet nearby suggests that either the dusts are produced within the region from multiple source bodies or the dusts are material created outside the region somehow got trapped in this region. Whichever the case might be, there has to be some active process that confines material around D68. But we are not sure which physical process(es) is/are responsible for creating and disturbing this ringlet [58]

Furthermore, Cassini observed sometime between 2012 and 2015, a periodic brightness variation in a region D ring which was earlier more or less featureless. The intensity and wave number of the pattern seemed to decrease with time. Headman et all (2015) proposed that the structure was created by some event early December 2011 that disturbed the orbital motions of the ring particles. They suggested that differential orbital precession transformed the structure into a spiral pattern in the dense part of the ring. For micron-sized and ice rich region their estimation of total impulse to produce the pattern was 5×10^9 kg m/s This required momentum could be acquired by the rings through collisions with a cloud of cometary debris of sub-micron size . For this to happen the debris particles much be sub-micron grains. Another possible caused of the observed feature could be electromagnetic perturbation of the rings. Since the small particles that dominate the visible appearance of this ring can have large charge-to-mass ratios their dynamics can be significantly influenced by electromagnetic forces as discussed in the earlier section. For a micron sized an electric field about 20mV/m can give enough impulse over a timescale of one orbital period and 0.4mV/m for long duration perturbation. [56]

Again sometime in between 2014 or 2015 a series of bright clumps different from the earlier observations appeared within D68. These clumps suggest that they are composed of particles with a narrow (sub-kilometer) spread in semi-major axis. The event that triggered the formation of these bright clumps is still unclear. M.M. Hedman,(2019) suggested that fine material was released by collisions into or among larger objects (up to 20 meters wide) orbiting close to. [62]

3.3.3. E ring:

The E-ring extends from 3 to 8 RS near the equatorial plane. The E ring consists of micron-sized [19] and sub-mm-sized grains particle. The distribution of dust in the E ring follows a power law (Kempf et al., 2008) indicating that nano-meter grains are the dominant particles [61]. These nm and μm sized charged dust plays important role in the dusty plasma of the E ring [58].

Pre-Cassini models of Saturn's E ring failed to reproduce its peculiar vertical structure. After the discovery of an active Enceladus plume(Figure 6) the relevance of the directed injection of particles for the vertical ring structure of the E ring becomes clear.

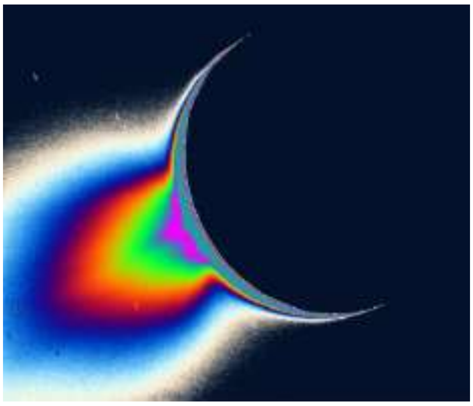

Figure 6: Fountains of ice particles from plumes of the south polar regions. Enceladus feeding the Saturn'sdusty E ring. (Porco et al., 2006). Courtesy : pg. 840 of [7]

However, simple models for the delivery of particles from the plume to the ring predicted a too small vertical ring thickness and overestimated the amount of the injected dusts. S. Kempf et al. (2010), numerical simulations of grains leaving the plume and populating the dust torus of Enceladus show that particles >0:7 lm can only escape to the E ring if their initial speeds exceed the Enceladus three-body escape speed of 207 km [63]. It is now established that most parts of the E ring are formed by the geyser of water molecules ejected at the south pole of Enceladus [46,61,64].

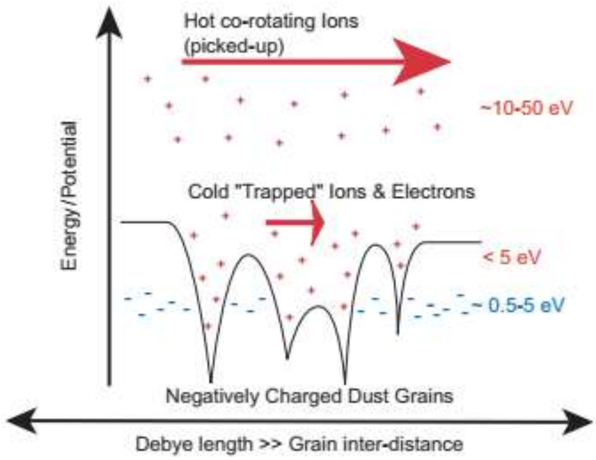

Figure 7: Ionized electron-ion pairs start with low energies, become trapped to a large degree by the steep potential gradients near the charged dust grains. Eventually, part of the ion population becomes accelerated by the co-rotation electric field around Saturn, and attain the larger co-rotation energies and can move more freely through the dusty plasma. Courtesy: Pg 1805 of [61]

The charge of the dust in the E-ring as estimated by Kempf et al., (2006) is a few volts negative inside 7 RS and positive outside the orbit of Rhea. The electrical potential cavities of the few volts negatively charged E-ring water-rich dust grains interacts with the Keplerian population of cold ions and established $\vec{E} \times \vec{B}$ pick-up of freshly ionized particles by the rotating magnetic field of Saturn. This is possible because the local potential gradients near the dust grains are stronger than the large-scale co-rotation electric field [61]. The physical process is summed in the the diagram below fig. 7.

The difference of the electron and ion densities near Enceladus indicates that dust particles did absorbed significant number of electron [61] and got charged. This is a case of dust charging as have been discussed in the earlier section The charged dust particles near the equatorial plane can interact with the dense inner plasma-disk surrounding the E-ring interact trough electromagnetic forces as a collective dusty plasma. This implies that there is a relationship between the gravitational moving magnetospheric plasma disk and the SKR modulation [62].

In the E ring neighbouring particles distance is more than a Debye length. As such, the plasma shields each dust particle separately and can therefore be treated as an electromagnetically isolated ensemble of dust grains. Thus E ring in Saturn's magnetosphere is good place for studying the dust charging mechanism DPP in Saturn's rings.

3.3.4. The F ring:

The F ring discovered in September 1979 by Pioneer 11 is the narrowest of all the Saturn rings. It contains intertwining particles of large and small sizes[68]. It is a dynamic ring whose structure of varies on short time scales and over azimuthal distances. Some unique and puzzling features of F ring are the ring's narrowness, multi-stranded appearance, clumps, kinks, apparent braiding, and the fact that it has a satellite orbiting on either side of it [67, 72, 75].When it was first observed by voyager I it has three strands, each ∼20 km in width, whichappeared to be parallel at some longitudes but with while in voyager II observation it has five strand

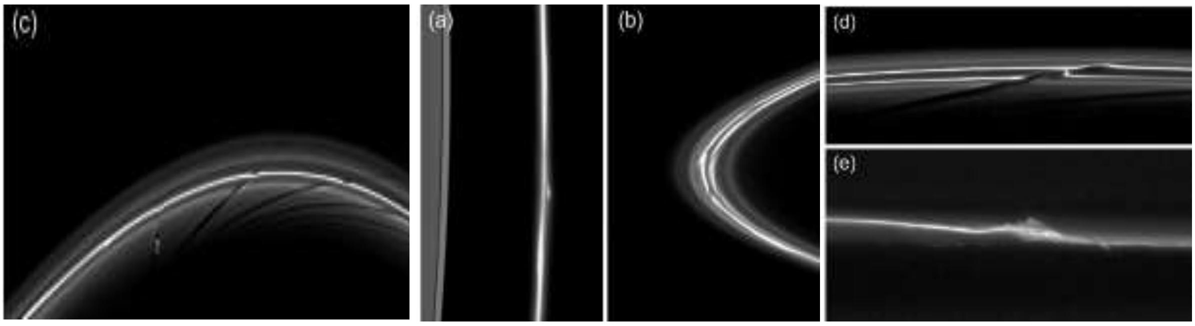

Figure 8.(a) Image taken on 2007 February 10 showing the edge of the A ring (left) and ∼5◦ of longitude of the Fring with bright features and azimuthal structure. (b) Image taken on 2007 October 25 showing **multiple strands** and azimuthal structure at the F ring ansa (c) Image taken on 2010 June 1 showing ∼17◦ of longitude of the F ring with multiple strands; the perturbing action of Prometheus (lower left) creates regular channels in the ring material interior to the bright core. (d) Image taken on 2008 September 30 showing the local effect of a recent passage by Prometheus (e) image taken on 2006 September 25 showing irregular radial and azimuthal features in the F ring core. Courtesy : pg. 341 of [72]

components – one bright and four faint. The strands consists of a single core with one or more wrapped spiral structures (resulting from sheared collisional jets) on either side. The width of the core as per Lane et al., (1982) is <3 km [73] , 10 km [68, 76] ~ 100 km, 100m [77]. On either side of the core are broader, more-diffuse features that seem to emanate from the core to radial distances of ∼400 km and are at a variety of angles to it. These “jets” of material are thought to be the result of low velocity, 1 ms^1 collisions between the core material and objects orbiting nearby [72] The core contains ‘kinks’, ‘knots’, ‘braids’, and ‘clumps’ [72] of centimetre-sized particles, with an envelope of micron and sub-micron ‘dust’ extending inward about 50 km.[71,76]. The structure of the core changes on timescales ranging from hours to years [74]. Showalter et all. (1992) proposed that the F Ring core contains an large objects, 100 -1000m that could sustain the ring up to this day. Showalter (1998, 2004) proposed that transient bright features are dust clouds formed by meteoroid bombardment, whereas some suggested that collisional grinding of larger bodies are responsible for formation of the dust clouds are produced the local [16]and the materials of F ring. [66]

The F Ring is located near the Roche limit [17-19, 25, 29, 69-71] within the inner part of Saturn's magnetosphere, which contains dense plasma torus. The dust surrounding this plasma can get charged from it. The rotation of the plasma torus suggests that cold plasma is electro-dynamically coupled to the charged ring-dust particles. [71] The variation of dust size distribution and its relationship with the dust state implies a complex dusty plasma dynamics related to the dynamics of the grain aggregation and the shattering processes near the F ring. [76] However, the magnitude of the charge grains cannot be accurate estimated as the plasma parameters themselves are not well understood [7, 32].

Since the Charged grains can be perturbed by the planet’s magnetic field (with different magnitude depending on the grain's charge-to-mass ratio) even a weakly charged grains strongly influenced the dynamics of the F Ring [71,76].

3.3.5. G ring:

Ihe first evidence for the existence of the G ring was given by Pioneer 11 in 1979 and was first observed by the voyager. It is located at168,000 km from Saturn’s centre and is beyond the Roche limit. It has a thin layer of mostly microscopic particles of between 1 to 10^3 μm in size [80] and 1 to 10 micrometres dust grains. It also contains larger (centimetre- to meter-sized) bodies whose total mass is equivalent to that of a ~100-meter-wide ice-rich moonlet [77-79]. M. Hedmanet al. suggested that collisions among the larger bodies generate dust that forms visible arc (localised bright feature) and the rest of the G ring. These dusts subsequently drift outward to populate the rest of the G ring [77].

During the pre-Cassini era the G rings was thought to be the remnants of a larger satellite that once orbited at the present G rings’ location. Showalter et al. (1992) suggested since it would not be possible for the microscopic dust of the G ring to survive for these years there must be a separate ‘parent’ bodies that are continually replenishing them. Also, since it is located beyond the Roche limit the possibility of it being formed through aggregation was ruled out. These parentsbodies are estimated to be atlest 0.1 – 1 km in size. They proposed that these parent bodies are the remants of a moon about 1-10km that was disrupted by a catastrophic impact in the early years of the Saturn system. As such the G is just the cloud of dusts of a remaining remnant of the moon. [78]

4. Saturn’s magnetosphere:

The magnetosphere is an area of space, around a planet, that is within the planet's magnetic field.Much of the current knowledge about the Saturn magnetospheric was provide flybys of Pioneer 11 in the late 70s and the two Voyagers in early 1980 spacecraft’s.

The sources of Magnetospheric plasma in the Saturnian system are (i) External source (the solar wind) and (ii) internal sources. [96] The voyager era established that most of the plasma in Saturn’s magnetosphere comes from the rings, the icy satellites and Titan. However, the dominant heavy ion was not identified.[91] Cassini provided us with more detail data about the magnetosphere. It is now established that ions of water and oxygen are the main constituent of the plasma. Figure 9aand 9b are is a Post-Voyager and Cassini era illustration of Saturn’s magnetosphere respectively.

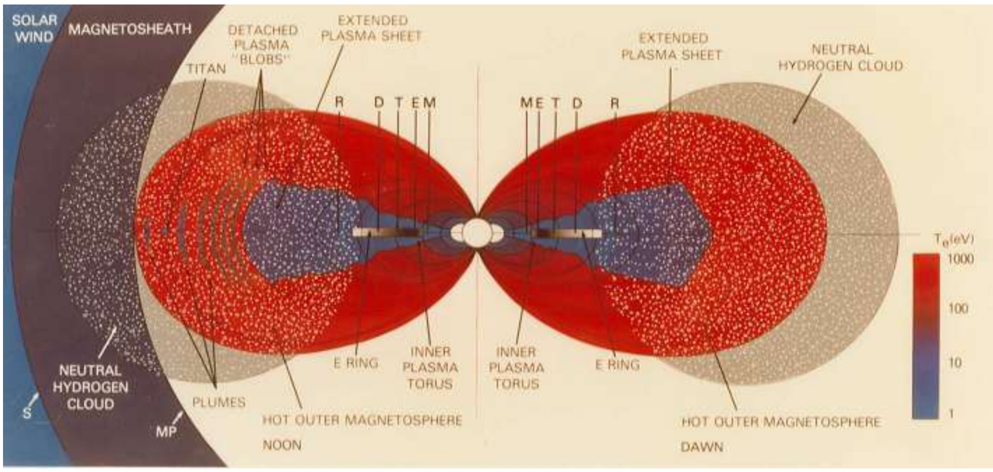

Figure 9a: Cold regions arecolored blue, regions of intermediate temperature arepurple (blue plus red), andthe hot regions are red. Thesatellite positions (M, E, T, D,and R for Mimas, Enceladus,Tethys, Dione, and Rhea,respectively), E ring (grayshaped rectangular region),neutral hydrogen cloud (circular region with white dots),and magnetopause boundary(MP) are displayed. Courtesy : Pg.3 of [91]

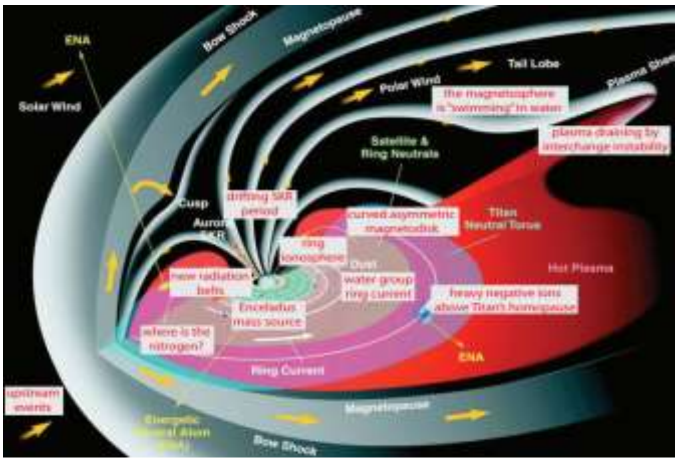

Figure 9b: Some of the new discoveries made by the Cassini science. Courtesy : Pg.3 of [91]

4.1. Sources of plasma in the inner magnetosphere:

The sources of magnetospheric plasma are characterized by different ion composition and dynamics, as well as different plasma densities and temperatures, which reflect different source, loss and transport mechanisms. The different process of plasma production are meteorite impacts on ring particles, photo-ionization of the neutral ring atmosphere, the ionosphere of Saturn and possibly cross-magnetic field diffusion from the ring-dust torus. [96]

4.2. Magnetospheric plasma profile:

Using the plasma electrons and positive ions data of the pioneer 11, Voyager I and Voyager II Bridge et al (1982) categorised the plasma in the Saturnian magnetosphere into four regions:
(i) The shocked solar wind plasma in the magneto sheath (between about 30 and 22Rs)
(ii) Variable density region (between 17 Rs and the magnetopause)
(iii) An extended thick plasma sheet (between 17 and 7 Rs) and
(iv) Inner Plasma Torus sheet (between L = 7.5 to at least L = 2.7) [79]
The sources of Magnetospheric plasma in the Saturnian system can be categorised into (i) External (the solar wind) and (ii) internal sources (Saturn's ionosphere, the ring system, the inner icy satellites, and Titan). [93]
Out of the four regions mentioned above the inner plasma torus fall within the Saturn ring system.There are three distinct internal sources of plasma: the upper atmosphere of Saturn (dominated by atomic hydrogen), the icy-satellite/ring system and associated neutral-gas cloud (dominated by water products), and Titan.But our focus would be only on the icy-satellite and ring. But this does not meant that the atmosphere of Saturn, Titans external sources has no contribution at all[4]. In fact some solar wind ions do enter the magnetosphere through the tail, and interstellar neutrals, the atoms populating the regions between stars, may enter Saturn's magnetosphere and become ionized therein. [75]

4.3. Inner Plasma Torus(IPT):

Bridge et. al. (1982) using the measurements of electron density derived the spatial distribution of plasma densities estimated that ITP extends inward from about L = 7.5 to at least L = 4.5 [81]. The dominant part of the ITP lies between 2.5 and 8 Saturn radii (1 RS = 60,268 km) from the planet, with a north-southward extension of 72 RS. [86]. IPT as a "region of low electron temperature (as low as 1 eV), high equatorial densities (as high as100/cm^3), and reduced scale height (as small as 0.2 Rs)"[64]. This region is coupled to the ring system and icy satellites as the main sources of plasma, [93] At L = 2.7, the plasma density was 100 O^+ / cm^3, [81]. The plasma sphere is dominated by hydrogen ions H^+ and water group ions W^+ O +, OH^+, $H2O^+$, and $H3O^+$ [77, 78]

4.3.1 Plasma sources of ITP:

Bridge et. al. (1982) suggested that since ITP spatially overlaps Tethys, Dione, Enceladus, G and E rings, and possibly extends upto the A ring they could be the sources of plasma produce through sputtering from ice-covered surfaces. John Richardson (1989) too suggested that Saturn, the rings, the inner icy satellites (Mimas, Enceladus, Tethys, Dione, and Rhea), the large moon Titan are all direct and/or indirect sources of neutrals and plasma. From the atmosphere of Saturn and Titan the ions, electrons and neutrals can escape form plasma. The escaping ions and electron form the direct sources while the escaping neutral atoms and molecules get ionized by solar UV radiation or collisions with electrons and ions and add up the plasma population. Besides, bombardment of the icy satellites and rings by sunlight, plasma, and micrometeorites could knock atoms and neutrals off the surface and get ionized to contribute to the plasma population.

Enceladus:

Now it has been confirmed beyond doubt that the main internal plasma source in the IPT is the Enceladus. The neutral water and nitrogen molecules emitted from the plume of Enceladus undergo charge exchange, photoionization and electron impact ionization [Arridge et al., 2012] to produce plasma ions. These ions are subsequently processed by photolytic and radiolytic processes to produce H+ and a variety of water group ions such as OH+ and O+ that are collectively referred to as W+. [97]

M.K.G. Holmberg et al (2012) analysed the ion density and velocity of Saturn's from the Cassini Radio and Plasma Wave Science (RPWS) and Langmuir probe (LP) gave the following points about the magnetospheric plasma.

i. The plasma density is maximum, (105 cm^3,) at direct Enceladus plume passages confirming this moon to be a source of volatiles for the E-ring.

ii. The general equatorial density structure slowly decreased outwards from Saturn, and faster towards the planet.
iii. Excluding the Enceladus flybys, the density is higher near Tethys. This suggests that Tethys could also be a plasma source.
iv. No density peaks are recorded at the orbits of Mimas, Dione, and Rhea. They suggested that the mechanism of plasma production in ITP to be photo- and impact ionization processes. [86]

4.3.2. Dion and Tethys as plasma sources:

Apart from Enceladus the other natural satellites, the rings, and Saturn's atmosphere act as minor internal plasma sources [96]. Dione and Tethys as plasma sources are supported by several in situ measurement. The solar wind plasma analyser on board Pioneer 11 detected a large torus of oxygen ions (0_2^+) of densities >10 cm^{-3} inside the orbit of Rhea over the radial distance range of 4-7.5Rs and over the Dione and Tethys oxygen ion densities are found to be about 50cm^{-3}. [83] This indicates that the orbits of these moons are surrounded by plasma torii. The maximum plasma density near the equator of the L-shell of Dione was estimated to be 20–25 cm^3 and consisted mostly of ions (possible N+, O+, OH+ or H_2O^+ .) With a mass number around 16 amu[96].meteorite impacts on ring particles, photo-ionization of the neutral ring atmosphere, the ionosphere of Saturn and cross-magnetic field diffusion from the ring-dust torus are the possible mechanism of these plasma production. [90]

4.3.3. Main rings:

The ion mass spectrometer on Cassini revealed the existence of a layer of thermal plasma consisting of atomic and molecular oxygen ions (O+ and O + 2) [78] over the main rings A and B. The tenuous atmosphere of molecular oxygens surrounding the main rings are also believed to be a plasma source. The ring ''atmosphere'' and ''ionosphere'' plasma are likely produced by UV photosputtering of the icy rings and subsequent photoionization of oxygen molecule to create a centrifugally driven, outward-flowing plasma, which combines with the torus plasma in the A ring.

Within a radial distance RS 2.292 , corresponding the outer edge of A ring no magnetospheric particles were detected.This indicates that the dense ring A and B act also as the sinks for energetic electron Besides, O_2^+ ions that are produced north of the ring plane are eventually lost to the rings. [64] The electrons losses in the dense rings play a dominant physical process near the planet (L < 2.3)..The decrease in electrons in the main rings vary inversely with ring optical depth suggests that the electrons are photoemission of magnetically conjugate particles in sunlight on the far side of the rings [78]

4.3.4. F ring:

From the Radio and Plasma Wave Science (RPWS) investigation on board Cassini during Saturn orbit injection on July 1, 2004 Wahlund, J.-E., et al. (2005) found a a dense (<150 cm3) and cold (< 7 eV) plasma torus outside the visible F-ring .This torus of partly dusty plasma does not perfectly co-rotate with Saturn suggests that the cold plasma is electro-dynamically coupled to the charged ring-dust particlesand interact with dust or plasma or with neutral gas or plasma ions.[95]

5. Dusty plasma effects:

5.1. Mass transport within the Saturn rings:

The fluctuation of dust charge due to the fluctuation of the plasma electron and ion currents fluctuation can lead lead to an orbit perturbation and spatial or radial diffusion.[22] The radial transport of dusts can sometimes be very rapid as their motion in the magnetosphere is non Keplerian. Since the radial transport caused the redistribution of angular momentum within the rings it plays important role in the evolution of the Saturn ring system. [10]

Dust levitation makes the transport of grains across the ring plane possible as the grains that are blown off the surfaces initially move around the planet in their gravito-electrodynamic orbits. Smaller particles are affected by both the gravitational and electromagnetic [36]. In the region of the 'spokes' most of them got absorbed on the surfaces of the larger objects of the B ring. Consequently, there is a net radial transport of grains in the given size ranges outward or inward (as the case may be) across the ring plane in the entire region occupied by the spokes. This pattern of differential radial transport of grains of different sizes is mostly controlled by the relative velocities of the plasma and the grains of different sizes [35].

The particles within the magnetosphere ‘mirror’ rapidly across the magnetic equator, and drift both longitudinally and radially inward. Energetic electrons can get absorbed when they do not have enough energy to go through the dust [92] they are thus absorbed into the surfaces of satellites and ring particles. At the A ring’s edge and more so in the outlying rings, the erosive and radiation damaging effects on the ring material of this bath electrons and ions is prominent [64].

The formation of the expanded neutral OH cloud and broader oxygen cloud are thought to be the direct consequence neutral transport due to dusty plasma effects such as charge-exchange interactions, electron impact ionization, molecular dissociation, ion-neutral collisions, and neutral-neutral collisions within the Enceladus torus.[94].

5.2. Mass transport between the rings and the Saturn atmosphere:

Another important effect of dusty plasma is the transport of charged dust particles fromt/to the main rings to/from the Saturn ionosphere along the planetary magnetic field.Cassini spacecraft observations over Saturn’s rings in 2004 indicated the presence of a water-product atmosphere which is composed of icy grains and is partly ionized by solar ultraviolet radiation around the rings. J. O’Donoghue1 et al.,(2013) suggested that there is “interactions between Saturn and its main rings through charged, nanometer-sized ejecta particles.” [90]They proposed that the charged material of the ring atmosphere are the cause of the observed pattern of features(extending across a broad latitude band from 25 to 60 degrees) in Saturn. [96]. Four year later in 2017, a nanometre-sized dust was detected in the D ring by the Cassini spacecraft during the “Grand Finale”. The most probable source for this dust population is the the D68 ringlet [52]J.-E. Wahlund et al (2017) suggested that there is electrodynamic interaction between the cold, dense and dynamic Saturn’s ionosphere and the charged D ring through planet’s magnetic field. Collisions between small dust grains and H atoms provide sufficient drag to de-orbit the dust, causing it to plunge into the atmosphere over ~4 hours. [53] This results in an ionospheric ion outflow along magnetic flux tubes leading to plasma structuring[98].It estimated that at least “~5 kg s-1 of dust is continuously precipitating into the atmosphere [52].”

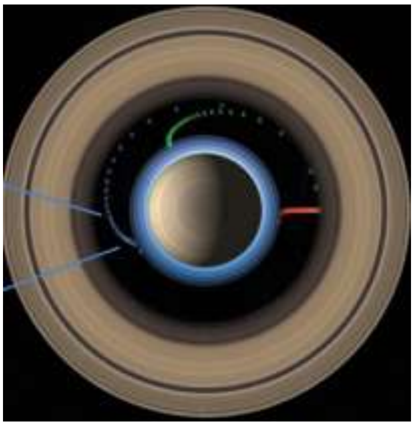

Figure10a: Schematic view of the nanometer-sized ring ejecta environment in the vicinity of Saturn. Courtesy : Pg. 1 of [91]

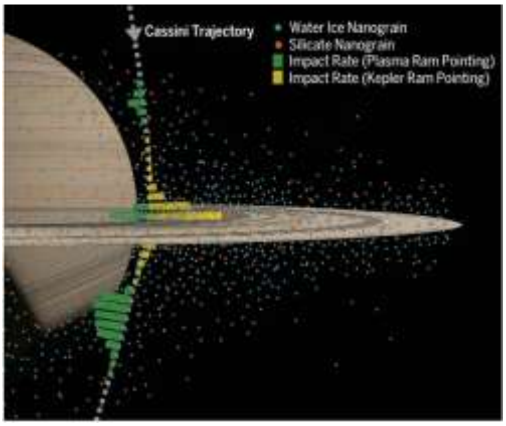

Figure 10b: Model trajectory of a dust particle in three frames of reference, as collisions with exospheric hydrogen degrade its velocity. Courtesy : Pg. of [52]

6. Discussion:

Saturn's magnetosphere comprises a unique plasma environment [84] the interplay of plasmas of various origins and properties with the solar wind, planetary rotation, and orbital motions results in several different chemical and dynamic plasma regions. [4]. Thus, Determination of the rings' ages depends on loss processes, including the transport of dust into Saturn's atmosphere.

In spite of so much theoretical and experimental research that have been done no comprehensive theory about the Saturn rings is obtained. Many of the dusty rings observations still await their theoretical explanation (s). All that is known is that "dusty plasma processes govern the large-scale dynamics and structures of some of Saturn's rings and give rise to smaller-scale dynamical and structural features in many rings, including some in which electromagnetic forces do not greatly influence the large-scale, time-averaged properties" [1]. For instances, the rotation of the Plasma in Saturn's magnetosphere can be slowed from the co-rotation speed due to mass loadings [86] In dusty rings Plasma supply through pickup of ions and charge exchange are the key processes.[93] the ion speeds can be significantly reduced by the electric fields (generated by the collisions between ions and dusts) for high dust density large thickness of dust distribution. [86] We believe that understanding the dusty plasma effects in the Saturn rings could explain many of the observations and lead us to the understanding of the origin, evolution, ages etc. of the Saturn's various rings.

In other words, understanding of the various non gravitational forces acting on the charged particles of Saturn can lead us to understanding of Saturn's rings.

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