The azimuthally-averaged mass density is $\sigma_s = \tau_s \eta m/\pi s^2 = 1.5\times10^{-6}$ g cm^{-2} for $\tau_s = 0.1$ and the fractional area covered, $\eta = 0.05$ (ref. 6). If spokes exist below the Voyager contrast or resolution level, which seems likely, then our estimates can be regarded as a conservative lower limit. The lifetime of a spoke is $t_L = 9\times10^3$ s (ref. 7). The average charge of a spoke particle is not well known. Goertz[8] argues that $Q = -200\ e$ whereas Eplee and Smith[9] suggest that Q can be as large as $Q = -10{,}000\ e$. Here e is the electronic charge. The ring surface density σ_R is taken to be 60 g cm^{-2} (ref. 2). The effective radial mass transport velocity is

$$w \approx -1.2\times10^{-10}\left(\frac{Q}{e}\right)^2\left[\left(\frac{L_S}{L}\right)^5-\left(\frac{L_S}{L}\right)^{7/2}\right]\text{cm s}^{-1}$$

At $L = 1.8$ the velocity w is $7.0\times10^{-12}(Q/e)^2$ cm s^{-1}. The transport velocity due to the ring viscosity is given by $-\nu/r$ with $\nu \approx 20$ cm^2 s^{-1} s a typical value in the B-ring[1]. At $L = 1.8$ this is $\sim 2\times10^{-9}$ cm s^{-1}. Thus mass transport due to electromagnetic angular momentum coupling to Saturn is of comparable importance even for $Q/e = 30$ except very close to the synchronous orbit ($L = L_s = 1.86$). We note that the radial velocity of the spoke particles $v_r = -4.3(Q/e)$ cm s^{-1} at $L = 1.8$. The electromagnetic angular momentum timescale, as defined by equation (8), becomes

$$\tau_R = 2.2\times10^{18}\left(\frac{Q}{e}\right)^{-2}L^6\left[1-\left(\frac{L}{L_S}\right)^{3/2}\right]^{-1}\text{ s}$$

At $L = 1.8$, and for $Q/e = 100$, this yields about 5×10^9 yr. Viscous time scales, $\tau_{\text{vis}} \equiv r^2/\nu$, on the other hand give $\sim 2\times10^{11}$ yr.

The viscosity of a particulate disk is a complex and not well understood function of the ring mass density[2]. In general, there will always be some particle diffusion due to collisions, as well as the systematic radial drift $-\nu/r$. We will discuss this elsewhere. Here we just note that a steady-state solution of the transport problem, including viscous and electromagnetic effects, will display a minimum in the B-ring near, but outside of the synchronous orbit. Figure 1 shows the optical depth variation of the B-ring on a linear scale. It clearly shows such a minimum. If the optical depth of the B-ring was originally constant at ~2.5, corresponding to the values outside the 'synchronous minimum', then the equivalent displaced mass corresponds to 9×10^{20} g, about 13% of the current ring mass. The timescale for displacing this mass can be estimated from the above considerations, and is significantly less than the lifetime of Saturn. If the electromagnetic angular momentum transport process really works as efficiently as we have calculated (this depends on the charge, mass and elevation of spoke particles) this implies that Saturn's ring system is not primordial, or that spoke activity has not been continuous.

We have shown that the sporadic elevation of small dust particles above Saturn's ring, and their subsequent reabsorption, provides a mechanism for angular momentum coupling to the planet, provided the dust particles are charged. There is clear evidence that the spoke particles are, indeed, charged. Then the ring loses angular momentum inside synchronous orbit and thus moves towards the planet, whereas it gains angular momentum and moves away from the planet outside synchronous orbit. In this picture, the outer boundary of the B-ring follows quite naturally.

At $L = 1.9485$, angular momentum is transferred by strong gravitational torques to the moon Mimas (2:1 resonance). In this way, excess angular momentum is removed, and the ring material is clamped in place. The positional agreement between the outer B-ring boundary and the Mimas 2:1 resonance is very good.

One may even speculate that the A-ring has evolved away from this resonance under the past influence of spoke-like phenomena, or even due to the current action of weak activity below the Voyager observational threshold.

Using reasonable values for the charge of the spoke particles, and observed ring and spoke properties, we have shown that the timescales for B-ring evolution due to the momentum coupling discussed here are comparable with, or even smaller than, viscous evolution timescales.

This effect, combined with some stochastic spreading, should produce a minimum in the optical depth of the ring near, but just outside synchronous orbit. Such a minimum seems, indeed, to exist. We also note that the transport due to the momentum coupling should affect the viscous instability discussed in connection with the formation of ringlets[2] as well as the resonantly driven density and bending waves. Since spokes are observed only in the outer B-ring this may be less important for the waves in the A and C rings.

In addition, the momentum coupling introduced across the ring by the processes discussed here, may lead to instabilities by themselves. This will be discussed elsewhere (C.K.G. and G.E.M., in preparation).

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Plasmatization and recondensation of the saturnian rings

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One major puzzle from the ground-based and Voyager observations of the saturnian system concerns the presence of the E ring and its possible relationship to the icy satellite, Enceladus[1–3]. Several issues concerning the surface property and interior condition of Enceladus remain unresolved if it is the main supplier of the E-ring particulate matter. Here we explore the intriguing alternative that the mass supply and orbital configuration of the E ring may be derived from a mass and momentum coupling between the A ring and the tenuous E ring a process of plasmatization and recondensation of the A-ring icy material. In the same way, the C ring could be replenished by the B ring. In this new view, plasma transport has a very important role in the dynamical evolution of the saturnian ring system.

The possible importance of plasma transport in the redistribution of the mass of Saturn's rings has been discussed elsewhere[4–8]. The basic idea is that charged particles situated at the ring plane would be lost to the planetary surface by field-aligned motion if the radial distance is smaller than a certain critical value. For charged particles initially in co-rotation, for which the magnetic moment is negligibly small, the critical radius is $R_c = 1.625R_s$ (where R_s is the radius of Saturn); and for keplerian-launched charged particles with their magnetic moments defined by the difference between the co-rotational speed and the keplerian speed, the critical radius is $R_c' = 1.525R_s$, as determined by Northrop and Hill[5] using the Z3 magnetic model[9] and the J_2 and J_4 terms[10] of the gravitational field of Saturn.

The critical radius R_c is located near a sharp transition in brightness in the B ring at $R \simeq 1.64R_s$, and the second critical radius R_c' is situated only 20 km away from the inner edge of the B ring[4-7]. Plasma transport could therefore be instrumental in defining the ring mass distribution. Note that although Northrop and Hill considered the relevant charged particles to be tiny icy grains with a very large value of q/m (where q and m are, respectively, the charge and mass of the particles), I stressed the role of large water cluster ions in the mass-loss process (or siphon flow)[6]. In principle, these two types of charged particle are the same as long as the charge-to-mass ratio is effectively very large. In the following we refer to the charged particles under discussion as water cluster ions and their parent neutral particles as water clusters, to distinguish their ring origin. If the loss rate of the water cluster ions remains the same throughout the existence of the ring system, which may be as short as 10^8 yr from dynamical considerations[11-14], the average mass injection rate from the ring plane for $R < 1.63R_s$ to the planetary atmosphere would be $\dot{\sigma} \simeq \sigma/10^8\,\text{yr} \simeq 3.2\times10^{-14}\,\text{g cm}^{-2}\,\text{s}^{-1}$ or $\dot{M} \simeq 4\times10^6\,\text{g s}^{-1}$ if the surface density is $\sigma \simeq 100\,\text{g cm}^{-2}$. This large influx of water ions and molecules could be very important in modifying the ionosphere of Saturn (by electron depletion), as discussed elsewhere[6,15,16].

One consequence of the ionization of the ring material is that the water cluster ions will be accelerated or decelerated to co-rotational motion depending on where they are produced. For those stably trapped in field-aligned motion (that is, not lost to the planetary atmosphere because of the siphon flow effect), they may be directly reabsorbed by the rings during their bounces across the ring plane. As the water clusters recondense on the surfaces of larger ring particles, they will be decelerated or accelerated to keplerian motion. This implies a very efficient method of exchange of angular momentum between the rings and Saturn. For orbital distances larger than the co-rotation distance ($R_{syn} = 1.86R_s$), there will be an acceleration effect with angular momentum transfer from Saturn to the rings, whereas the opposite effect holds for $R < R_{syn}$ (ref. 8). It can be estimated that the ring torque from ionization and recycling of the ring material is of the order of $\dot{L} \sim 5\times10^{-21}\,\text{g cm}^2\,\text{s}^{-1}$ as far as the A ring is concerned[17]; this value is comparable to the torque in the opposite direction from gravitational interaction with the shepherding satellites and the co-orbital satellites[11,18]. It is thus clear that the electrodynamic effect from ring plasmatization could be of importance in holding the A ring in place.

In addition to direct recondensation of the water (ion) clusters, another way to transfer mass and angular momentum is through accretion of the particles flung into elliptical keplerian orbits or ballistic escape orbits after their neutralization from the ring plasma. For cold ring plasma (as indicated by the brightness variation at $1.63R_s$), the keplerian orbit of a neutralized particle will be determined by the radial distance (R_o) at neutralization and the angular momentum (L_o). From conservation of angular momentum and the condition of force balance of a particle in circular keplerian motion, the radial position of this 'projected' particle (R_k) can then be determined.

Because the planet itself represents a perfect absorber, particles with flight paths intercepting Saturn will be lost after the first launch. This condition then defines the inner limit of the inward projection of the plasmatized ring matter (originating from $R < R_{syn}$). Our computation, taking into account the J_2 and J_4 terms of the gravitational field, indicates that this limit is given as $R_{k,min} = 1.258R_s$ for $R_{o,min} = 1.691R_s$. If the C ring forms by the accretion of ring material injected from the B ring to balance the loss through siphon flow, the consideration of the angular momentum budget would imply that the inner boundary of the C ring should be given approximately by $R_{k,min}$. The value of $R_{k,min}$ is indeed almost the same as the observed inner edge of the C ring taken to be at $1.235R_s$. The slight discrepancy could be explained, for example, by the thermal spread of the water cluster ions or collisional scattering effects.

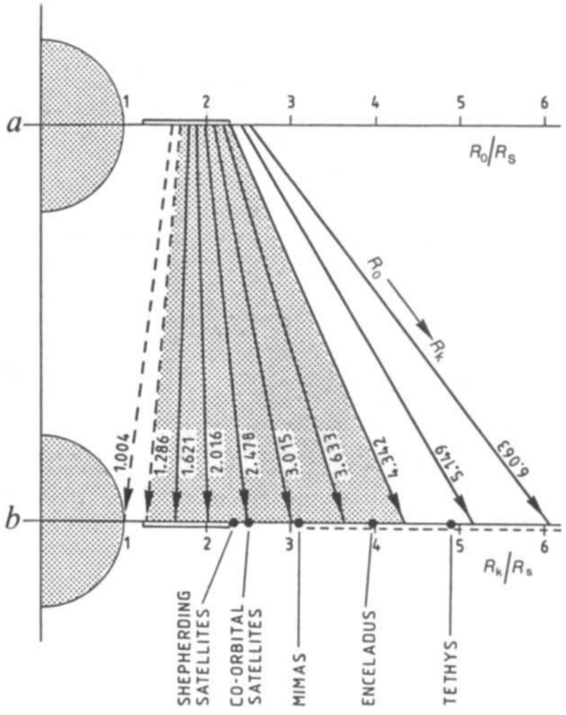

Fig. 1 Angular momentum projection of the ionized ring material in the form of charged particles with $q/m \to \infty$ after their neutralization. Conservation of angular momentum allows the determination of the orbital radius (R_k) of a particle flung into keplerian orbit (b) from its radial distance (R_0) at neutralization (a). Because of the absorption effect of the planet, neutral particles ejected inside $R = 1.69\,R_s$ from co-rotating motion will be lost after the first launch. This process may define the inner edge of the C ring. At the same time, material ejected from the A ring would define the spatial extension of the E ring via angular momentum redistribution.

The E ring, which has a peak brightness near the orbit of Enceladus, has generally been thought to be the product of mass ejection from the surface of this icy satellite[1-3]. The E-ring particles, with an average size determined to be a few micrometres[19], have very short lifetimes against energetic charged particle sputtering and plasma drag (outward) transport[20,21]. Both mechanisms typically have timescales of the order of 10^3–10^4 yr. If the E-ring system is to be maintained as a permanent structure, it will require a steady source[22]. Below, we consider the possible contribution from the material ejected from the main ring system.

As shown in Fig. 1, the particles neutralized from the ring plasma at different locations in the A ring will have angular momentum corresponding to R_k between $3.0R_s$ and $4.0R_s$. This means that interception of these particles in ballistic flight by the E ring beyond $4R_s$ will lead to braking of the outward motion of the charged E-ring particles as a result of interaction with co-rotating thermal plasma. Furthermore, accretion of these water clusters will lead to replenishment of the material lost by the surface sputtering effect. The mass erosion rate of the E ring may be estimated as follows. For an average optical depth of

$\tau_E \simeq 3\times10^{-7}$, a total area of $S_E \simeq 1.7\times10^{21}$ cm^2 and an average particle size of $d \simeq 3$ μm, the total mass erosion rate can be given as $\dot{M}_E \simeq -0.6$ g s^{-1} if the sputtering timescale is 10^4 yr.

The injection rate and accretion rate of the water clusters from the A ring are more difficult to derive because the whole sequence of ionization, neutralization and final collisional assimilation must be very complicated. But we could use the C ring as a reference point in the sense that the maintenance of the C ring is conditioned by balancing the mass loss rate (through siphon flow) with the mass accretion rate (from the B ring):

$$\frac{\tau_c S_c}{t_s} = \frac{\tau_B S_B}{t_a} \tag{1}$$

where t_s is the loss timescale and t_a the accretion timescale. From equation (1), $t_a \simeq (\tau_B/\tau_c)t_s$ or $t_a \simeq 20t_s$ (for equal areas: $S_c \simeq S_B$) as the optical depth of the C ring is $\tau_c \simeq 0.1$ and that of the B ring $\tau_B \simeq 2$. When applied to the E ring, the effective value of the accretion timescale of matter injected from the A ring should be scaled by the probability of interception (P). As $P_c \simeq 0(1)$ and $P_E \simeq 0(10^{-5})$, the total mass accretion rate will be

$$\dot{M}_E{}^* \sim \frac{10^{-5} f \tau_A S_A}{t_a} \tag{2}$$

where $f = 100$ g cm^{-2} is the factor converting optical depth to surface density, $\tau_A \simeq 0.5$, and $S_A \simeq 10^{20}$ cm^2. Thus, for $t_a \simeq 2\times10^9$ yr, $\dot{M}_E{}^* \simeq 0.8$ g s^{-1}; and it can be seen that $\dot{M}_E{}^* \simeq |\dot{M}_E|$. This much simplified calculation therefore shows that the E-ring complex could be partially maintained by accretion of the A-ring water grains as well as acquisition of the corresponding angular momentum. Thus, the E ring could have a lifetime much larger than 10^4 yr as estimated before.

In general, the plasmatization model of the rings requires the presence of many water clusters in the ring system. To maintain the loss rate of $\dot{M} \simeq 4\times10^6$ g s^{-1} and with photoionization as the only net ionization effect (timescale assumed to be $\sim10^9$ s), the average number density of the water clusters (assumed to contain 1,000 H_2O molecules each) would be $n_{\rm cluster} \simeq 10^7$-$10^8$ cm^{-3} in the ring plane with a thickness $\lesssim 10^2$ km. Their existence can be tested by remote sensing methods or by *in situ* measurements. Neglecting the interception effect by the E ring, from equation (2) we have the total escape flux $\dot{N} \simeq 10^5\,\dot{M}_E/m_{\rm cluster} \simeq 2\times10^{24}$ s^{-1}. It is of interest to search for these water clusters and ions (after their re-ionization) in the magnetosphere of Saturn using appropriate ion and neutral detectors/analysers.

Let us consider the physical constraints on the generation of cluster ions. Hypervelocity impact experiments have shown that tiny condensates form as part of the impact ejecta (E. Grün, personal communication). One reason for their formation may be related to the supersaturation (and hence recondensation) effect in the adiabatically cooling outflow of the expanding impact vapour. Secondary cluster ions have also been detected and analysed in ion sputtering experiments[23]. In the D-region of the Earth's ionosphere, water cluster ions are very abundant as a result of ion-neutral reactions[24]. As for the required number density of such large cluster ions, we shall adopt the assumption that there is a population of cool plasma stored in the so-called 'free-zone' just above the ring plane[25]. Taking the vertical displacement of the centre of the azimuthally symmetrical magnetic field to be $\sim0.04\,R_s$ (ref. 9), the total volume of the plasma disk so formed can be estimated to be $V \simeq 1$-8×10^{28} cm^3. Assuming that the ring plasma contains mainly electrons and singly ionized cluster ions, we have the total mass loss rate caused by electronic recombination given as $\dot{M}_c \simeq \alpha_e m_c (n_c^+)^2 V$, with α_e as the electronic recombination coefficient and n_c^+ as the number density of the cluster ions in the free-zone. In laboratory studies[26], α_e for water cluster ions $H_3O^+(H_2O)_n$ with $n = 0$-6 has been determined to be rather large ($\sim10^{-5}$ cm^3 s^{-1}). Now, equating $\dot{M}_c$ to $10^5\,\dot{M}_E$ we find $n_c^+ \simeq 2$-11 cm^{-3}, which is reasonably small. (Taking the larger value of $n_c^+ \simeq 11$ cm^{-3}, which may be more appropriate for a thin plasma disk, the corresponding electronic recombination time is of the order of 10^4 s, which is a fraction of the bouncing period of the cluster ions and the planetary rotation period.)

In the estimate of the accretion probability P_E, it was assumed that the water clusters pass through the E ring only once. In fact, in the present scenario, the water clusters emitted at radial distance less than $2.34R_s$ will be in periodic elliptical orbits, and they could return to the E-ring region repeatedly until lost by ionization or impact. For instance, for $R_o = 2.20R_s$ (and $R_k = 3.70R_s$), there will be about 10 returns if the ionization time is about 2×10^6 s. This effect will increase the P_E value by a factor of 10 and leads to a reduction of the total recombination rate by a similar factor. This means the momentum coupling between the A ring and the E ring should require only a moderate amount of mass ejection from the A ring. Note that, besides water clusters, atoms and molecules like H, O and H_2O (and thus their ionized counterparts) could in principle perform the same function in mass and momentum transfer. The role of large water clusters and cluster ions is emphasized here, as they would imply a very small value of electron number density ($n_e \lesssim 10$ cm^{-3}) along the magnetic flux tubes in the siphon flow process, whereas for atomic and molecular ions, $n_e \simeq 10^3$-10^4 cm^{-3} is required. More quantitative work should clarify this point further.

Finally, we note that the proposed scenario of the plasmatization and recondensation of the saturnian ring system is reminiscent of the model of Alfvén[27] which relates the mass distribution of the rings to the condensation process in a rotating plasma. The important difference is that the present model applies to the redistribution of ring matter after the initial formation of the ring system. We also note that other electromagnetic angular momentum transfer processes such as that discussed in the case of charged dust particles[28] could be important and complementary to the one described here.

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