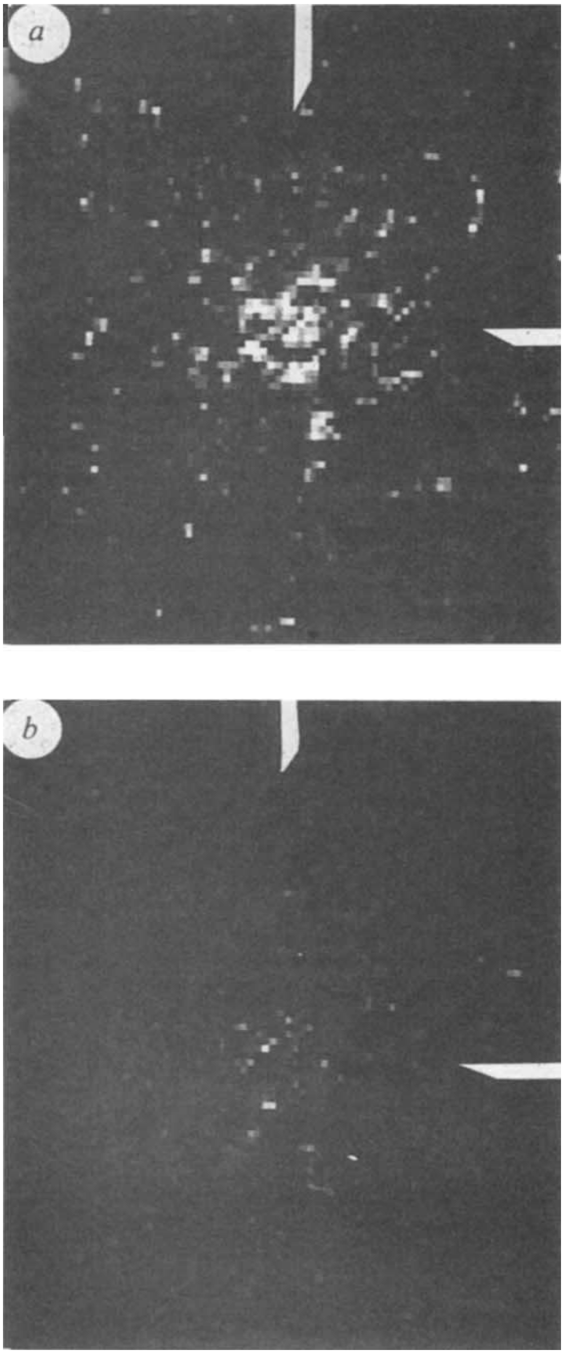

Fig. 2 Lyman-α images of the hydrogen coma of comet Halley taken at *a*, 00:00 30 November UT (active phase) and *b*, 04:00 28 November UT (inactive phase). The vertical and horizontal dimensions of the photographs are both 2.5×10^6 km (at the comet's position). The comet nucleus (located at the intersection of the white marker wedges) is at (right ascension, declination) = (01 h 41 m, 15° 50′) on the 1950.0 star atlas in *a* and (01 h 56 m, 16° 50′) in *b*. The distances of comet Halley from the Sun and Suisei are *a*, 1.50 and 0.84 AU, and *b*, 1.53 and 0.83 AU. The faintness of this image suggests that the outburst phenomena overwhelm the other activity of this comet.

encounters the comet, on 8 March 1986, we would expect the shell to have a more sharply defined form due to the shorter photodissociation time. Our continuous observations over the next several months will allow detailed spatial and temporal studies of the hydrogen coma in comet Halley.

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Electromagnetic angular momentum transport in Saturn's rings

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The observed 'spokes' in Saturn's rings have been interpreted as consisting of elevated, sub-micrometre sized dust particles[1]. Arguments in favour of this interpretation are, for example, the photometric properties (spokes are dark in backscattered, bright in forward scattered light), the dynamics (approximate keplerian rotation) and lifetime (less than half an orbital period). We show here that submicrometre dust particles sporadically elevated above the ring are subject to electromagnetic forces which will reduce their angular momentum inside synchronous orbit and increase it outside. When the dust is reabsorbed by the ring the angular momentum of the ring is decreased (increased) inside (outside) of synchronous orbit. For the case of the spokes in Saturn's B-ring we estimate that the timescale for transporting ring material due to this angular momentum coupling effect is comparable to the viscous transport time or even smaller. We suggest that the minimum in the optical depth of the B-ring at synchronous orbit is due to this effect.

The temporal evolution of Saturn's rings is believed to be primarily determined by the angular momentum transport as a consequence of collisions between the differentially rotating ring particles[2]. In addition, mass erosion effects, meteor impacts, resonances with satellites and moonlets and density waves[3–5] are important. So far, electromagnetic effects have not been considered to be important because the electromagnetic forces on the typical big (~1 m) ring particles are small compared with the gravitational force of the planet[6]. Only submicrometre dust particles are significantly influenced by electromagnetic effects. We now discuss a potentially very important indirect mechanism whereby electromagnetic forces can affect the angular momentum transport in the ring and hence its long-term evolution. This indirect mechanism works through the small dust particles constituting the spokes. Note that if the spokes do not consist of elevated dust, but only of a rearrangement of dust particles in the ring plane, our mechanism would probably not be relevant. However, as mentioned earlier, the available evidence favours elevated dust, and then it is easily demonstrated that the effect is important. The spokes of Saturn have an optical depth of

$\tau \approx 0.1$, and cover a fraction $\eta \approx 0.05$ of the B-ring between $1.7 R_p$ and $1.9\ R_p$ (planetary radii). The mean particle size is $s = 3 \times 10^{-5}$ cm. The total mass in the spokes is thus

$$M_s = 0.7 \frac{4\pi}{3} s \tau \rho_s \eta R_p^2$$

For a nominal material density of the spoke particles $\rho_s = 1\ \mathrm{g\ cm^{-3}}$ we obtain $M_S \approx 3 \times 10^{13}$ g (see also ref. 6). We argue below that during the time a spoke particle is elevated it has an average radial velocity of $\sim 10^2\ \mathrm{cm\ s^{-1}}$. Thus the total mass of the B-ring (7×10^{21} g) could be transported over a distance of $0.2\ R_p$ in 10^8 yr.

Consider a dust particle of mass m ejected at a radial distance r out of the ring plane. It has a charge Q. Its velocity is $v_r \hat{r} + v_\phi \hat{\phi}$. If the planetary magnetic field corotates, the particle will be subject to a Lorentz force

$$\vec{F} = m \frac{d\vec{v}}{dt} = Q[v_r \hat{r} + (v_\phi - \Omega_p r)\hat{\phi}] \times \frac{\vec{B}}{c} - \frac{G M_p m}{r^2} \hat{r} \qquad (1)$$

where Ω_p is the rotation rate of the planet, G the gravitational constant and c the speed of light. From the ϕ component of equation (1), we get (ϕ is in the direction of the ring particle rotation)

$$\frac{d}{dt} \mathscr{L} = v_r \frac{a}{r^2} \qquad (2)$$

where $\mathscr{L} = r v_\phi$ is the specific angular momentum of the particle. We have assumed a dipole field, near the equatorial plane this is

$$\vec{B} = -B_0 \left(\frac{R_p^3}{r^3} \right) \hat{z} \qquad (3)$$

and have introduced

$$a \equiv \left(\frac{Q B_0}{mc} \right) R_p^3$$

For Saturn $B_0 = 0.2$ G, and the planetary radius is $R_p = 6 \times 10^9$ cm. When the particle is reabsorbed by the ring after a mean time, t_L, it has changed its specific angular momentum by an amount

$$\Delta \mathscr{L} = \int_0^{t_L} \frac{d\mathscr{L}}{dt} dt \qquad (4)$$

Since we are concerned here with particle populations, it is convenient to introduce the angular momentum per unit surface area

$$\tilde{\mathscr{L}} \equiv \sigma \mathscr{L} \qquad (5)$$

where σ is the surface density. In the following, we shall use subscripts R and S for rings and spokes, respectively. The rate of change of ring angular momentum can then be easily calculated.

Since in the absorption process of spoke material the total angular momentum must be conserved, the only angular momentum lost by the system is that calculated from equations (2)-(5). Hence,

$$\frac{d\tilde{\mathscr{L}}_R}{dt} = \frac{d\tilde{\mathscr{L}}_S}{dt} \qquad (6)$$

The rate of change of the specific ring angular momentum is then

$$\frac{d\mathscr{L}_R}{dt} = \frac{\sigma_S v_r a}{\sigma_R r^2} \qquad (7)$$

from which we may compute the timescale for angular momentum change of the ring

$$\tau_R \equiv \mathscr{L}_R \left(\frac{d\mathscr{L}_R}{dt} \right)^{-1} = \frac{\sigma_R r^2 \mathscr{L}_R}{\sigma_S v_r a} \qquad (8)$$

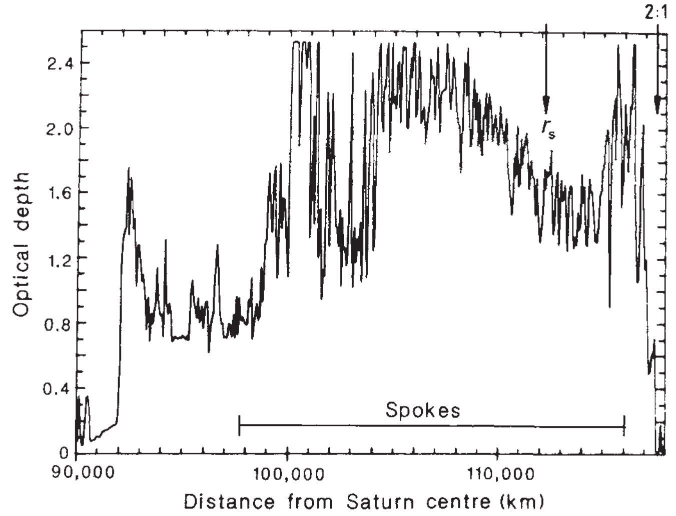

Fig. 1 Optical depth variation in Saturn's B-ring[10]. The horizontal line indicates the observed extent of spoke activity. The synchronous radius and the Mimas 2:1 resonance positions are also shown.

For all practical purposes, we may put $\mathscr{L}_R \equiv \mathscr{L}_K$, the Kepler value $\sqrt{GM_p r}$. The radial evolution of the ring material is characterized by a velocity

$$w \equiv \frac{2r}{\mathscr{L}_R} \frac{d\mathscr{L}_R}{dt} = \frac{2 \sigma_S v_r a}{\sigma_R r \mathscr{L}_R} \qquad (9)$$

The radial velocity at impact can be calculated from equation (1).

$$v_r \approx -\left(\frac{Q B_0}{mc} \right) \frac{R_p^3}{r^2} \left(\frac{v_\phi}{r} - \Omega_p \right) t_L \qquad (10)$$

To simplify matters we assume that the azimuthal velocity of the particle is everywhere the keplerian velocity. This is a good approximation as long as $\Delta r / r \ll 1$. Thus the effective radial mass transport velocity is (we use $L \equiv r / R_p$)

$$w \approx -\left(\frac{Q B_0}{mc} \right)^2 \frac{R_p}{L_S^5} \frac{\sigma_S}{\sigma_R} \left[\left(\frac{L_S}{L} \right)^5 - \left(\frac{L_S}{L} \right)^{7/2} \right] t_L \qquad (11)$$

Inside the synchronous orbit ($r_s = R_p L_S$, where $\Omega_k = \Omega_p$) the mass transport is inwards, it is zero at synchronous orbit and outwards beyond r_s.

We note that the direction of the mass transport is independent of the charge sign. The reason is that inside synchronous orbit keplerian dust particles move faster than the corotating magnetic field and, therefore, always lose angular momentum to the planet (irrespective of the charge sign) whereas they gain angular momentum from the planet outside synchronous orbit. This change of angular momentum of one component determines the evoluton of the whole ring material. If the small particles remained in the ring they would quickly collide with, and be absorbed by, the large ring particles. In that case t_L would be small. If the elevated particles were bigger $\sigma_S = 4/3\ \rho_S s \tau$ increases. However, if the charge is proportional to particle radius, s, (implying constant potential), w is inversely proportional to m, and the significance of the effect is reduced accordingly. The angular momentum coupling to the planet is thus most significant if small dust particles can be elevated above the ring plane, that is, where spoke-like activity occurs in the ring. These considerations suggest that the spokes in Saturn's B-ring, so far regarded as a curious phenomenon without major consequences, may significantly affect the long term evolution of the B-ring itself.

To make some numerical estimates of the effect, we consider the following. The spokes in Saturn's B-ring presumably consist of ice grains with an average size of $s = 3 \times 10^{-5}$ cm ($m = 10^{-13}$ g).

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, $\tau_{vis} \equiv r^2/\nu$, 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 $R_c = 1.625 R_s$ (where R_s is the radius of Saturn); and for