Long build up → Short active → Sudden death
with low → phase with high → due to runaway
luminosity → luminosity → instability

The short active phase is probably connected with energy generation in a process suggested by Paczyński[17]: when the density of the disk exceeds $0.1M/R_c^3$ the self-gravity of the disk becomes important (dashed line in Fig. 2) and local instabilities, similar to the Jeans instability develop. If the optical depth is so large that the cooling scale is longer than orbital period the instabilities increase velocity dispersion in the gas. This produces turbulence, thereby enhancing viscous stresses which produce heat and drive accretion. The possibility that active galactic nuclei switch on and off quasi-periodically seems to be consistent with both observation evidence[18] and theoretical ideas[14].

Note that in the case of some exotic galactic objects (SS433, for example[19,20]) which are conventionally modelled by accretion disks orbiting black holes, one has $m \ll 0.01M$. For such objects, the runaway instability does not work. In fact, the Roche lobe overflow mechanism has in this case a stabilizing effect[21]. More information on the relativistic theory of thick accretion disks can be found in ref. 22, the theory of accretion disks was reviewed recently in refs 23–25.

Finally, let us make another estimation which supports the previously discussed results. The simplest way to show the importance of runaway instability is to discuss a very thin pressureless, non-self-gravitating accretion disk. Such a disk has its inner edge R_{in} at the circle corresponding to the marginally stable orbit for a free test particle orbiting the black hole. It is located at $R = R_{\text{MS}} = 3R_{\text{G}}$. The orbits of free particles with $R \leq R_{\text{MS}}$ are unstable. Pressureless matter cannot stay on such orbits and must fall down the hole. Let us denote the surface density of the disk by $\Sigma(R)$. Take a small amount of mass δM from the inner edge of the disk and put it into the hole. The change in the location of the inner edge will be $\delta R_{\text{in}} = \delta M/2\pi\Sigma(R_{\text{MS}})R_{\text{MS}}$ while the change in the location of the marginally stable orbit is $\delta R_{\text{MS}} = \delta M R_{\text{MS}}/M$. Obviously, the runaway instability occurs when $R_{\text{MS}} + \delta R_{\text{MS}} \geq R_{\text{in}} + \delta R_{\text{in}}$, as in this case some matter is placed on unstable orbits after the mass transfer. This condition is equivalent to

$$\Sigma(R) \geq \frac{M}{2\pi R^2} \equiv \Sigma_{\text{run}} \tag{14}$$

for $R = R_{\text{MS}}$. Note, that the surface density which corresponds to the equality sign in equation (1) could be of the same order as the one in a disk which is marginally unstable with respect to the self-gravitational fragmentation perturbations of the Jeans type[17], $\Sigma_{\text{BP}} = A_s(H/R)M/2\pi R^2$, where H is the disk thickness and the dimensionless parameter A_s is >10 (but its precise value is not known, Paczyński[17] estimates $A_s \approx 16$). The condition for the runaway instability to be more important than the fragmentation instability is $\Sigma_{\text{run}} < \Sigma_{\text{BP}}$ or $(H/R) \geq (1/A_s) \approx 0.05$. Non-self-gravitating disks models of Muchotrzeb and Paczyński[7] have $(H/R) = 0.05$ for the critical accretion rate at R_{MS} and $(H/R) > 0.05$ for higher accretion rates at $R = R_{\text{MS}}$.

In this simple example all the previously discussed aspects of the runaway instability are clearly visible: (1) runaway instability is important for at least some realistic accretion disk models of active galactic nuclei; (2) both general relativity and self gravity of the disk are important for discussing this instability; (3) the criterion for occurrence of the runaway instability is $\delta R_0 > \delta R_{\text{in}}$. Only in the pressureless case it is $R_0 = R_{\text{MS}}$, in general $R_0 < R_{\text{MS}}$ and this shows that the pressure effects are also important.

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Equatorial confinement of thermal plasma near the rings of Saturn

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In the unique environment of the rings of Saturn, because of a combination of the magnetic field geometry and the meteroid impact ionization at the ring plane, a thin plasma disk having a total thickness of no more than a few per cent of the planetary radius might exist in the vicinity of the ring system. The radial transport of this ring plasma to larger radial distances may act as an important source of the thermal plasma in Saturn's magnetosphere. I suggest here that the recent observations by the Voyager 2 Plasma Science team are not inconsistent with this scenario.

Because of the extensive nature of the rings of Saturn, important coupling between the ionosphere and the ring plane is expected. For example, the interception of the photoelectron–H^+ pairs from the top-side ionosphere would act as a sink for the ionospheric plasma as well as a source of the neutral atomic hydrogen cloud in the vicinity of the rings[1]. Photosputtering[2] and meteroid impact[3] on the ring plane could also provide a significant supply of neutral atoms and ions in the ring environment. The survival of the neutral atoms and molecules in keplerian orbits and especially, the ions trapped in bouncing motion along the planetary magnetic field, depends largely on the optical depths of the rings and the geometry of the dipole field.

It is possible to store a population of ions with near-equatorially mirroring pitch angles[4] just under or above the ring plane—that is, if the dipole axis is slightly tilted and offset from the planetary centre as indicated by the Pioneer 11 observations[5] and the preliminary report of the Voyager finding[6]. A recent re-evaluation of the magnetic field measurements at Saturn by Connerney *et al.*[7] has indicated that Saturn's planetary magnetic field can be best described by an axisymmetric octupole model. While a tilt of the pointing axis of the magnetic moment from the planetary rotation axis could be ruled out in this new model, a northern offset of the plane of minimum magnetic field by $\sim 0.04R_s$ is still possible. In this sense, the wedge-shaped 'free zone' proposed by Goertz *et al.*[4] would have to be modified to be a thin slab no thicker than $0.08R_s$ just above the ring plane. The possible presence of such a thin disk of H^+ and O^+ ions is very interesting because the occurrence of radial spokes of enhanced concentration of fine dust particles in the B ring[8,9] and the Saturn electrostatic discharge (SED) in the vicinity of the rings[10,11] might all be related to electrodynamical processes resulting from dust–plasma interaction with the 'free zone' plasma as the main physical ingredient (see refs 4, 12). The confirmation (or otherwise) of its formation could therefore place an important constraint on the development of theories of the Saturn ring–magnetosphere interaction.

As it is not possible to probe the plasma environment of the rings by direct measurements, remote sensing techniques such as radio occultation measurements would be useful, provided the electron density in the 'free zone' is large enough ($n_e \gtrsim 10^3\ \mathrm{cm}^{-3}$). However, a very special edge-on view of the ring plane by the Earth is perhaps required for such spacecraft observations. Thus, only remaining method seems to be *in situ* measurements of the thermal plasma distribution just outside the ring edge at $2.3R_s$.

With the ring system as a strong plasma source of the inner magnetosphere, it is possible in principal to trace the plasma population fed from the free zone. This is because in a rapidly rotating planet, the scale height of an equatorially confined plasma disk could remain almost constant over a wide range of radial distances[13–15]. More specifically, as shown by Siscoe[15], the mirror point latitude λ_m at radial distance r of an ion created at radial distance r_s and mirror point latitude λ_{ms} can be expressed as:

$$\frac{\lambda_m}{\lambda_{ms}} = \left[\frac{(3\xi_s^2+2)x}{3\xi_s^2+2x^5}\right]^{1/4} \tag{1}$$

where $x = r/r_s$ and $\xi_s = (V_c - V_k)/V_c$ with V_c and V_k as the co-rotating and keplerian velocities at r_s. At $r_s \approx 2.2R_s$, $\xi_s \sim 0.2$; thus for outward diffusing plasma $x > 1$ and

$$\frac{\lambda_m}{\lambda_{ms}} \sim \frac{1}{x} \tag{2}$$

This means that the scale height ($r\lambda_m$) of the ring plasma disk, if extended to a radial distance of $3R_s$ or more, would remain the same in the absence of other external perturbation effects (for example, pitch-angle scattering and charge-exchange loss). It is therefore interesting to check the Voyager 2 plasma observations during the ring plane crossing at $2.88R_s$ (ref. 16) to determine whether there indeed exists a thermal plasma disk confined to the magnetic equator with a scale height of no more than $0.04R_s$. The preliminary report by the Voyager 2 plasma science team[17] has found the scale height of the O^+ (assumed) ions to be $0.2R_s$ at the interval of the ring plane crossing. Such a small scale height, as noted by the experimenters, is not consistent with the thermal temperature measured as 10 eV. One possible explanation[17] is that the observed equatorial confinement is facilitated by the formation of a pancake-like pitch-angle distribution dominated by equatorially mirroring particles. One possible source of such a thin plasma disk is the free-zone plasma transported outwards as a result of radial diffusion.

Due to the presence of tenuous particulate matter distributed in the narrow G ring and the diffuse E ring, the idea of free zone formation might be generalized to regions outside the A ring. In the optically thick parts of the ring system, the time scale of O^+ ion absorption is of the order of a few bounce periods ($t_B \sim 3\times10^4$ s) if the ring particles are not charged to surface potential $\gtrsim$10 eV. The corresponding loss time scale in the G ring would be $t_A \sim 10^5\ t_B$ if the average optical depth of the G ring is taken to be $\sim10^{-5}$ (ref. 8). The radial diffusion time scales in different regions of the saturnian magnetosphere are still not very well determined. On the basis of Pioneer 11 observations[18–20] of the G ring absorption effect of the energetic charged particles, the radial diffusion time scale across the G ring could be estimated to be $t_D \sim 3\times10^6$–3×10^7 (ref. 21). As $t_D \ll t_A$, the G ring, even with its mass mainly distributed in a thin layer of only 100 km[22], is insufficient to cause the formation of a thin plasma disk confined to the magnetic equator. In view of this, the observations by the Voyager 2 plasma instrument suggest the existence of a free zone in the vicinity of the main ring system.

There are processes which might lead to decay of the free zone plasma as it diffuses outwards to larger distances. For example, intermixing with the ionospheric plasma could increase the scale height of the thermal plasma disk; Coulomb collision time scale for 10 eV-oxygen ions having a number density of $100\ \mathrm{cm}^{-3}$ is $\sim10^6$ s, which is $\lesssim t_D$. Isotropization of the ring as it diffuses outwards is thus expected. Charge-exchange recombination also could be efficient in producing pitch-angle diffusion. That might be one reason why the thermal plasma at $r \approx 2.88R_s$ was not restricted to the magnetic equator as might have been expected. In any event, the Voyager 2 plasma data apparently do not contradict the idea of equatorial confinement of the ring plasma as a result of the axisymmetric magnetic field[4,21].

Frank *et al.*[23] have estimated the source strength of the oxygen thermal ions detected by the Pioneer 11 plasma instrument to be 10^{23}–10^{24} ions s^{-1}. In comparison, the meteroid impact ionization has been estimated as being about 10^{27} ions s^{-1} using the data available[24]. In principle, feeding of ~0.1% of the impact plasma into the free zone would be sufficient to maintain the thermal plasma population within 5–$6R_s$. The potential importance of the ring source of the heavy ions is that it provides an efficient mechanism of electrodynamical coupling between the rings and the entire magnetosphere. As recently proposed[25], a two-cell convection system may be established in the vicinity of the D ring as a result of the diurnal modulation of the photoemission rate of the ring particles. If a similar effect exists throughout the whole ring system, the co-rotation pattern of the magnetospheric plasma in Saturn's inner radiation belt might be modified. This point will be considered elsewhere taking into account the pertinent observational data.

Finally, recent studies[24,26–28] have indicated that the opacity discontinuity at $1.64R_s$ and the inner edge of the B ring at $1.52R_s$ could be related to the equatorial confinement effect of the ring plasma generated by meteroid impact and ionization of the neutral gas in the vicinity of the ring system. The thermal temperature of impact ions (assumed to be O^+ ions) is of the order of $\lesssim$10 eV. (E. Grün, personal communication) and the pick-up ions created in the neutral cloud have initial gyroenergies $\lesssim$2 eV. Thus, with enough energy resolution, plasma measurements such as those carried out by the Voyager PLS instrument could, in principle, elucidate the sources contributing to the thermal plasma disk, and also place important constraints on the ring electrodynamic models[24–28].

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