letters to nature

On the origin of Uranus' rings

DERMOTT and Gold[1] have proposed that the structure of the rings of Uranus[2-4] may be explained by a series of three-body orbital resonances with the satellites Ariel, Titania and Oberon. This mechanism has been considered in more detail[5,6], and it is found that the particular resonances involving Ariel–Titania and Ariel–Oberon pairs encounter difficulties in explaining the ring system. This has led to strong arguments against the part played by the Miranda–Ariel resonances, but we show here that such orbital resonant effects should not be completely discarded.

Aksnes[5] and Goldreich and Nicholson[6] have shown that the predicted radial positions of the rings disagree with those determined from observations, and even if orbital resonant effects are responsible for the formation of the rings, the Miranda–Ariel resonances should be the most important. Indeed, from the three-body resonant relation

$$qn-(p+q)n_{\mathrm{B}}+pn_{\mathrm{A}}=0 \qquad (1)$$

where p and q are integers and n the mean motions while the subscripts A and B denote the outer and inner satellites, it is observed that the orbital positions of Millis *et al.*'s ring 5, and Elliot *et al.*'s α, γ and ε_2 rings correspond closely with the Miranda–Ariel three-body resonances with $q=1$ and $p=10$, 9, 8 and 7, respectively[4].

However, Aksnes[5] and Goldreich and Nicholson[6] argued that it is unlikely that particles in these rings are trapped by such orbital mechanisms. This is because the Miranda–Ariel resonances allow only very small displacement ($\Delta a < 0.1$ km) from the radial positions of exact resonances and the rings all have widths (Δr) >1 km ($\Delta r \approx 1$–10 km for the α ring and $\Delta r \approx 30$–100 km for the ε_2 ring).

Although this is a strong argument against the possible part played by the Miranda–Ariel resonances in the formation of the Uranus rings we believe that such orbital resonant effects should not be discarded. For one thing, there is no compelling reason for orbital resonances to produce clustering of resonant particles if other dynamical effects are also involved (obvious examples are the Kirkwood gaps in the main asteroid belt). Also, while inelastic collisions among the resonant particles will tend to disrupt the orbital resonance[6], perturbation effects (larger amplitude of the oscillation in the orbital eccentricity, e) of the resonant particles might lead to mass accumulation in the neighbouring region.

Suppose originally we have a thin disk of small particles of millimetre size instead of a series of narrow rings. Inelastic collision between these particles will reduce their e values to essentially zero. In fact, without extra perturbation effects these particles will not interact any further and a flat disk structure seems to be the terminal configuration found in computer simulation experiments[7-9]. It has also been shown, however, that if proper perturbation effect is introduced such that the average e value is always larger than certain values capable of maintaining the collisional interaction between the particles, orbital focusing of the disk particles into a narrow ring is possible[9]. Therefore, it is tempting to speculate that the orbital perturbation effects on the particles trapped into the Miranda–Ariel resonances will help increase the e value of particles in the neighbouring orbits. As a result, there possibly will be formation of particle rings (or 'jet streams'[10]) at selective locations corresponding to orbital resonances.

Because of the larger particle density in these rings, the coagulation process will lead to larger particles as compared to those in other areas, which means that these ring particles will suffer less orbital decay. If there are metre-size objects formed in these rings, such a structure will be very stable against Poynting–Robertson effects and gas drag (if any). On the other hand, the orbital distances of the small particles in regions between rings will be gradually reduced. This disk population will eventually be intercepted by different rings and consequently a pile-up of the materials near the resonant positions will be established. Therefore, the three-body orbital resonances of Miranda and Ariel act mainly as a trigger for the formation of narrow rings, and not as a trapping mechanism of freely orbiting particles.

Such orbital focusing mechanisms incorporating the orbital resonance and Poynting–Robertson effects are similar to the effect proposed by Gold[11]. But in the present work the inelastic collision process is considered to be vital to the formation of narrow rings.

If the Miranda–Ariel resonances could account for the formation of Millis *et al.*'s ring 5 and Elliot *et al.*'s α, γ and ε_2 rings, the immediate question would be what causes the other series of rings, that is, Millis *et al.*'s ring 4 and Elliot *et al.*'s β, δ and ε_1 rings. Applying equation (1) and assuming that these rings are related to the three-body resonances of Miranda and an inner satellite not yet discovered, we find that resonance with $q=1$, $p=7$, 8, 9 and 10 could have the observed locations if the semi-major axis of the inner satellite is $\approx 1.03\times10^5$ km. For these resonances to have perturbation effects similar to the Miranda–Ariel resonances the mass of this new satellite should be similar to that of Miranda.

The sharply defined boundaries of the rings may be due to the nature of the narrowness of the resonances. This is because only particles in the vicinity of the $q=1$ and $p=10$ resonance of the Miranda–Ariel system (say) will be coagulated into larger bodies and retained in the near-neighbourhood of the resonance. The width of the ring should be larger than that determined by the resonance[6], however, as we expect certain 'leakage' of the particles to the inner region. But only more detailed study could tell how this would work. Another important question to be answered is about the eccentricity produced by the resonances. There is no reliable way to estimate the e values except by the numerical calculation performed by Franklin and Colombo[12] in the study of the Mimas resonant effect on the saturian ring particles. Similar calculations are now in progress and the results will be used to construct more quantitative model of the uranian rings.

Because we are still far from understanding the structure of the Uranus' rings, it may be important to search for alternative approaches to this interesting problem. The model presented here is basically an application of the concept of jet stream formation in the early history of the Solar System[10], but also offers the opportunity of observational test. Possible confirmation of the inner satellite predicted here will be of great interest in cosmogony.

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Solar-wind sputtering of the martian atmosphere

IN the sputtering process an incident particle beam loses part of its energy to recoil motion of target atoms, some of which may escape through a nearby surface. The sputtering yield, *S*, is defined as the number of atoms ejected per incident particle. In the Solar System, sputtering will occur whenever the solar wind, consisting mainly of $1\ \mathrm{keV\ AMU^{-1}}$ hydrogen and helium ions, strikes a material body. Many years ago, Wehner *et al.*[1] suggested that solar wind-induced sputtering of the lunar surface should be an important cause of erosion; recently, analyses[2] of returned lunar material have been interpreted quantitatively[3] in terms of such solar-wind sputtering. Mars provides another example of the interaction of the solar wind with a planetary body. However, in contrast to the lunar surface, the martian surface is largely protected from direct solar wind bombardment by its atmosphere. The primarily CO_2 atmosphere is thin by terrestrial standards but still opaque to the solar wind. We discuss here whether solar-wind sputtering of the martian atmosphere is a mechanism leading to significant mass loss.

As the solar wind collides with particles in the outermost portion of the atmosphere, it will cause atmospheric atoms and molecules to be sputtered in a manner similar to the case of a solid target. The magnitude of the effect depends on the extent to which such collisions actually occur. Although Mars lacks a significant magnetic field, the martian ionosphere may partially deflect the solar wind[4,5]. However, for sputtering to occur the solar wind need only reach the uppermost regions of the atmosphere (say, an altitude ≈ 200 km). In fact a distortion of direct solar wind flow into a flow 'around' the planet can actually increase the sputtering yield by increasing the length of the protons' trajectory in the layers most easily sputtered. Such enhancement is well known in the sputtering of solids at oblique angles of incidence. Furthermore, a substantial modification of the proton velocity profile from that in interplanetary space can be tolerated because the sputtering yield is not a strong function of energy.

Thus, we have assumed here that all the impinging solar wind is effective in sputtering. As the mechanism by which gaseous targets may be sputtered has not been previously considered, the present calculation also illustrates how one may estimate the rate of such processes in other potentially interesting environments (such as jovian moons). We shall evaluate the martian atmospheric mass loss by solar wind sputtering by analogy with models of sputtering of solid surfaces and by using empirical data for the lunar surface.

The martian atmospheric density at an altitude of 200 km differs by a factor of $\sim 10^{14}$ from that of common solids. However, the sputtering yield is not expected to be a function of target density. At lower densities the beam particle will, on average, penetrate a surface more deeply before generating a primary recoil. On the other hand, longer mean free paths allow secondary and tertiary recoils to escape more easily. In the upper atmosphere, the critical level, h_c, where the mean free path in the horizontal direction just equals the scale height, distinguishes approximately between a lower region of diffusive motion and an upper region of ballistic motion. If the solar wind ion interacts with an atmospheric molecule too far below h_c, the lower energy recoil cannot easily escape. Too far above h_c, the probability for generating a recoil is vanishingly small. This is analogous to the case of a solid where sputtered atoms originate from within the top few monolayers[6]. Of course, sputtering results from a complex network of sub-surface collisions[6] and this must also be true in the atmospheric example. To illustrate the scales involved for Mars, if we assume a 200 K isothermal atmosphere, we then obtain the scale $H \approx 10$ km and the critical level $h_c \approx 200$ km above the surface. The horizontal mean free path for a low energy recoil atom here is ~ 10 km, which may be compared with the corresponding interatomic spacing within a typical solid of ~ 2 Å.

A further possible difference between the sputtering of a solid and an atmosphere lies in the nature of the target binding forces. To escape from a solid target, a recoil atom must have sufficient energy to overcome chemical bonds. The appropriate surface binding energy is usually taken to be the sublimation energy whose value is a few eV. In an atmosphere, the binding is provided by the gravitational field. Thus, on Mars an energy of ~ 5.3 eV is required for a CO_2 molecule to escape from an altitude of 200 km and, therefore, these chemical and gravitational energies are comparable.

We conclude from these comparisons that sputtering should proceed in much the same way in the martian atmosphere as on the lunar surface. The sputtering-induced mass loss from the Moon has been estimated to lie in the range 1 to 13×10^6 atoms $\mathrm{cm^{-2}\ s^{-1}}$ which corresponds to the erosion of a surface layer of thickness 0.05 to 0.5 Å $\mathrm{yr^{-1}}$ (ref. 7). For this discussion, we adopt a yield of 7×10^6 atoms $\mathrm{cm^{-2}\ s^{-1}}$. This implies a sputtering yield of 3×10^{-2} atoms per solar wind ion.

These yields are consistent with measured values for solids involving keV projectiles and targets of mass similar to those of the constituents of the lunar surface[8]. Furthermore, those yields are consistent with the predictions of standard theoretical models[6,9]. (In these theoretical models of sputtering the binding of atoms in the bulk of the solid to their lattice sites is neglected. In this respect such theories are especially applicable to the treatment of gas targets.) Taking into account the fact that the solar wind flux is decreased by a factor of $(1.5)^2$ at the orbit of Mars, we estimate the mass loss from the planetary atmosphere to be 2.45×10^{24} CO_2 molecules $\mathrm{s^{-1}}$. Integrated over the course of 4×10^9 yr, the total mass loss becomes 3.1×10^{41} CO_2 molecules, a number independent of variations in the density of the atmosphere during its evolutionary history. This result may be compared with the present mass of the martian atmosphere of 4×10^{41} molecules (calculated on the basis of a ground level pressure of 7.5 mbar (ref. 10)).

Given the necessarily approximate nature of the present calculations, the interpretation of these results is that solar-wind sputtering must be considered as a potentially important mechanism for atmospheric mass loss from Mars. Such erosion processes will occur in much the same way in any environment where energetic particles strike a localised gas.

In conclusion, beside mass loss, sputtering may also lead to preferential loss of light elements and isotopes. This phenomenon occurs during ion bombardment of many alloys and compounds[11,12] and has been proposed[8] as the source of the isotopic fractionation observed on the surface of fine lunar dust grains subjected to solar wind bombardment. It may also occur in the martian atmosphere where certain isotopic anomalies have been reported[13]. Within a collision cascade[6], lighter isotopes recoil on average with higher velocities[12] so that they will be preferentially lost from the top of the atmosphere. The efficiency of this process for the lightest atmospheric constituents will be enhanced by the fact that their distribution extends

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