The Viscosity of Miranda

P.J. Thomas, R.T. Reynolds, S.W. Squyres and P.M. Cassen

Theoretical Studies Branch, NASA Ames Research Center, Moffett Field, CA 94035.

Voyager 2 images of Miranda reveal a significant history of geological activity. Overlying an apparently ancient, cratered terrain are assemblages of concentric ridges, scarps and dark banded material. Three regions of complex terrain are visible in the Voyager images, which cover virtually an entire hemisphere. These regions are typically $\sim 200km$ in diameter.

Although the concentric ridges have some similarity to the regularity of the grooved terrain on Ganymede, they are also associated with what appear to be extensive flow regions (possibly associated with internal melting) that, in some cases, have modified the geometry of the ridges. Finally, widespread brittle behavior is observed in the form of large faults, scarps and graben up to $15km$ deep.

We examine the problems that evolutionary thermal and structural models of Miranda must face, to provide an convincing explanation for such topographic complexity. The problems center around the requirement that such a small body ($R \sim 242km$) must have a sufficient heat generation mechanism to lower its viscosity substantially. It would generally be expected that a body of such size with such low ambient temperatures ($\sim 50\ K$) would have an extremely rigid surface. While the observed fault regions are consistent with a rigid surface, the high degree of sphericity of Miranda implies a low viscosity material, at least at some time in Miranda's past.

For viscous relaxation on a scale of $L \sim 100km$ to occur over a reasonable timescale ($\tau_r \lesssim 10^9 y$), the dominant viscosity μ determining viscous motion is given by

$$\mu \lesssim \frac{\tau_r L \rho g}{4\pi} \tag{1}$$

where for Miranda $g = 0.09ms^{-2}$ and $\rho = 1200kgm^{-3}$ (Tyler *et al.*, 1986) yielding $\mu \lesssim 10^{22} Pas$. Assuming a Newtonian viscosity law for ice (Weertman, 1970):

$$\mu = \mu_0 \exp\left(A^* (\frac{T_m}{T} - 1)\right) \tag{2}$$

with parameters appropriate to low-temperature ice $A^* = 25$; $T_m = 273K$; and $\mu_0 = 10^{14} Pas$ (Reynolds and Cassen, 1979), this is appropriate to a temperature T of $157K$, or a temperature $> 100K$ above the ambient temperature.

The two reference models for Miranda that we consider are that (1) the complex terrain was emplaced during a period of reaccretion following a disruptive impact (Smith *et al.*, 1986) in this case the energy required for resurfacing is produced by the release of the potential energy of the reaccreted fragments; or that (2) the complex terrain represents a disturbed region overlying a diapiric instability, similar to a mechanism proposed for the formation of palimpsests on Ganymede (Hale *et al.*, 1980). In the second case the energy required for resurfacing must have an internal origin, such as radiogenic heating or tidal deformation. These two models represent exogenic and endogenic formation models for the complex terrain, respectively. They also permit estimates of dynamic viscosities and associated emergy inputs required by these models.

If population statistics derived for the sizes of comet nuclei are valid for projectiles impacting on Miranda, it is conceivable that Miranda underwent a series of collisions with bodies of sufficient kinetic energy to disrupt it in the first Gy after its initial formation (Shoemaker and Wolfe, 1982; Smith *et al.*, 1986). This model implies that the final stages of reaccretion may have produced the observed terrain patterns by liberation of the gravitational potential energy of the disrupted fragments of the satellite.

While both models must be able to account for Miranda's high degree of sphericity, the reaccretion model faces a more stringent relaxation condition: that relaxation must remove all traces of the impact crater associated with the disruptive impact. Such a crater will have topographic harmonics associated with the rim with wavelengths much smaller than $100km$ and thus much longer relaxation times. For example, to relax crater rims with wavelengths on a scale of $10km$ in $10^9 y$ would require a viscosity of $10^{21} Pas$.

Unfortunately for this model, the energy that can be obtained from reaccretional heating for a body as small as Miranda is limited. The thermal energy retained by Miranda cannot be significantly greater than the binding energy, $\sim 2 \times 10^4 Jkg^{-1}$ which, given a specific heat for ice of $\sim 10^3 Jkg^{-1}K^{-1}$, predicts a maximum global temperature increase as small as $\sim 20K$. This estimate is in good agreement with more detailed models (Squyres *et al.*, 1986). Of course, local heating arising from point contacts between reaccreted fragments may much greater temperatures in small regions. Furthermore, disruption and reaccretion will dissipate much of this initial energy, tending to produce a more isothermal temperature profile (Ellsworth and Schubert, 1983). One final important problem that this mechanism must face is that, according to various evolutionary models of the icy satellites, radiogenic heating produces a maximum temperature profile for small satellites within the first $\sim 100My$ (Ellsworth and Schubert, 1983; Federico and Lanciano, 1983). This heat will also be dissipated by a cycle of multiple disruption and accretion, if such exists.

We can consider energy constraints on the endogenic model by calculating the ascent time τ_a for a buoyant inviscid sphere (our diapir model) of radius $a = 50km$ at low Reynolds number through a layer of thickness $L = 100km$:

$$\tau_a = \frac{3\mu L}{\Delta\rho g a^2} \tag{3}$$

we assume a density difference $\Delta\rho$ of $300kgm^{-3}$, appropriate to warm pure ice surrounded by material with the mean density of Miranda. Assuming $\tau_a \lesssim 10^9 y$ we obtain $\mu \lesssim 10^{22} Pas$, consistent with the determination above. This value is, however, very much of an upper limit, because Miranda's surface gravitational acceleration was assumed for g. The cooling time for such a diapir is $a^2/\kappa \sim 3 \times 10^8 y$ (where $\kappa \sim 10^{-6} m^2 s^{-1}$). For this ascent time (more reasonable than $10^9 y$ because of the presence of some cratering on the ridged terrain) we have $\mu \lesssim 10^{21} Pas$ which is appropriate, using the viscosity law above, to $T = 166K$, or $\sim 100K$ above Miranda's ambient temperature.

It is possible that extinct radionuclides such as ^{26}Al may have had a significant energy input into Miranda in the past. However, the half life of such elements (typically $\lesssim 10^6 y$) indicates that any resurfacing that occurred as a result would be substantially older than the observed, very lightly cratered terrain on parts of Miranda.

It appears to be clear that some energy source other than accretional heating is required to provide both the spherical shape of Miranda and the evidence of substantial viscous flow activity. The exogenic model requires enhanced temperatures after the last reaccretion, placing serious constaints on short term heating processes. In addition, it has a serious problem in accounting for the absence of small-scale impact features on much of Miranda's surface.

Given the difficulties in finding a suitable energy source capable of raising Miranda's global temperature to a sufficient extent to reduce the viscosity of pure ice adequately, it is possible that mobilization of ice clathrated with CO, N_2 or CH_4 by pressure-solution creep may be an important transport process. Under certain conditions, viscosities many orders of magnitude smaller than those calculated above may be produced by this mechanism (Stevenson and Lunine, 1986).

Since the temperatures determined here lie above the $H_2O.NH_3$ eutectic at $173K$, internal melting may have occurred to some extent. If the flow features were emplaced significantly after the accretional period ($\gtrsim 10^8 y$) then tidal heating alone remains as a plausible energy source. The energy required to produce increases in temperature of the extent calculated for the entire satellite is of the order of $10^{24} J$. If this was expended over the period of $3 \times 10^8 y$ mentioned above, a heating rate of $\sim 10^9 W$, which is $\sim 10^{-4}$ the heating rate associated with Io's tidal flexure. For Miranda no easily indenfiable orbital resonance can account for this enhanced heating (Squyres *et al.*, 1985). However, the effects of mutual satellite pertubations have not yet been considered in full complexity (Dermott and Nicholson, 1986). In conclusion, it should be emphasized that due to the inability of reaccretional heating to provide a important energy input for Miranda, any heating mechanism required by the endogenic model must also be required by the exogenic model.

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