is no further turbidity development and (ii) the observed order of magnitude change in turbidity of early spring is reproduced. It is found that the springtime-enhanced UV dose under the ice is independent of these limits.

Using the data developed above, we have calculated the temporal development of UV radiation at 305 nm transmitted through sea ice without a snow cover. Two cases are illustrated in Fig. 1. The lower curve shows the decrease in transmitted UV light that accompanies the increase in ice turbidity associated with the springtime warming. The upper curve was generated assuming the changing atmospheric ozone content calculated in (*1*). Thus, Fig. 1 demonstrates a 20-fold increase in under-ice UV radiance in early October resulting from the coincidence of the presence of the ozone hole and the period of relatively high transparency for sea ice. This clearly has implications for organisms living within and under the ice.

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Response: The response of organisms to enhanced levels of ultraviolet radiation depends on numerous factors, only one of which involves atmospheric radiative transfer. Trodahl and Buckley make the very important point that the transmission of Antarctic ice decreases as spring progresses. Since the "ozone hole" is primarily a phenomenon of early spring, this suggests that potential biological effects of the ozone depletion may be larger than otherwise anticipated. Trodahl and Buckley show that the "hole" of October 1987 was accompanied by an increase in radiation dose beneath the ice by a factor of 20 as compared with that in years before the appearance of the ozone depletion. Despite the percentage increase in irradiance beneath the ice, the absolute radiation level is still small, since the albedo of ice remains large. The change in ice transmission over time is cause for concern, although a central issue involves a comparison between the radiation doses and radiation tolerances of organisms beneath the ice. This topic clearly merits additional research.

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Ice Volcanism on Ariel

The report "Solid-state ice volcanism on the satellites of Uranus" by David G. Jankowski and Steven W. Squyres (*1*) proposes a novel emplacement mechanism for surface "lava" flows on Ariel and Miranda (on Ariel the "lava" is almost certainly a mixture of water and ammonia with perhaps additional components). Whereas terrestrial lava flows are a mixture of liquid and solids (crystals), Jankowski and Squyres propose that the flows on the Uranian satellites were entirely crystalline during emplacement. Existing models of lava flows are capable of accounting for the parabolic cross sections measured by Jankowski and Squyres. It is thus incumbent on the authors to demonstrate that their novel mechanism is really required.

For the past 20 years it has been clear to volcanologists working on terrestrial lava flows (*2*) that flowing lava behaves, not as a viscous fluid, but as a "Bingham" fluid with a well-defined yield stress. A Bingham fluid is one that responds elastically to applied shear stresses until the stresses exceed its yield strength, after which it flows as a viscous fluid. Bingham rheology characterizes a wide class of mixtures of liquids with solid particles, such as suspensions of clay in water, pigments in oil (paint), rock debris in mud, and crystals in melted rock (lava). Studies of lava flows on Mount Etna, Hawaii, and the moon (*2*) support the idea that erupted lava is a Bingham fluid with a yield stress ranging from about 10^3 to 10^5 Pa, depending on silica content. The most characteristic aspect of such flows is the approximately parabolic profile of their margins (with suitable corrections when slopes exceed the angle of repose), which can be directly related to the Bingham yield strength, Y_B. A formula valid for the profiles of lava flows, ice sheets, and debris flow lobes (all of which can be treated approximately as Bingham substances) relates the thickness of the flow's center h_0 to its horizontal width w:

$$Y_B = \frac{\rho g h_0^2}{w}$$

where ρ is the density of the flow and g is the planet's surface acceleration of gravity (0.27 m/s^2 for Ariel).

Jankowski and Squyres use photoclinometry to measure the profiles of five probable "lava" flows on Ariel. As they show, these profiles can be adequately fit by parabolas (except, of course, where the slope of the parabola becomes too steep—mass movement and regolith processes act to gently taper the flow's edges). They then propose a model that treats the extruded material as a Newtonian viscous fluid spreading from a central vent until cooling raises the viscosity past the point where flow is possible. They show that this model predicts parabolic flow profiles as long as the "lava" is moving. They then assume that the profile of the flow does not change as it cools and stiffens and derive a viscosity from the distance the flow has traveled within the cooling time (estimated from flow thickness and the thermal diffusivity of water ice).

A much more natural explanation of the morphology of Ariel's "lava" flows is that the extruded material is a mixture of liquid and crystals and that the parabolic profiles are an expression of the Bingham yield strength of the mixture at the time of solidification. All information about the rheology during extrusion and flow is lost during solidification and cannot be recovered without additional information. In Table 1 we have used the parabolic fits of Jankowski and Squyres and the equation above to deduce the yield strength of the flow material. These yield strengths vary from 6.7×10^3 Pa to 3.7×10^4 Pa, right in the midrange of terrestrial lavas. We do not

Table 1. Viscosities from (*1*) and Bingham yield stresses inferred from profiles in (*1*, figure 5).

Profile	Viscosity (Pa·s)	Bingham yield stress (Pa)
A	4.5×10^{15}	3.7×10^4
B	3.5×10^{15}	3.1×10^4
C	9.0×10^{14}	1.4×10^4
D top	1.1×10^{15}	1.4×10^4
D bottom	9.0×10^{14}	6.7×10^3

propose that Ariel's flows are silicates, only that an erupted mixture of water liquid and crystals or, more likely, a partially crystallized water-ammonia peritectic mixture (*3*), can account for the flow morphology without any appeal to special rheological mechanisms or heat sources. Jankowski and Squyres have provided some very interesting data on the morphology of flows on Ariel, but we feel that eruption of a liquid-crystal "lava" mush with a Bingham rheology offers a valid alternative to their proposed solid-state ice volcanism.

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Response: Melosh and Janes suggest that eruption of a liquid-crystal slurry with a Bingham rheology to the surface of the uranian satellites could produce thick convex-profile flows of the sort observed there. This mechanism was first suggested for H_2O volcanism in the Jupiter system by Wilson and Head (*1*). If such a material indeed has a yield stress on the order of 10^4 Pa, then the profiles we derived are also consistent with this rheology, just as we showed they are consistent with viscous flow entirely in the solid state.

In evaluating the implications of our profiles, we considered the possibility of liquid resurfacing. The reason that we prefer flow in the solid state has to do with the style of resurfacing on similar icy satellites in the Saturn system. The most relevant example is that of Enceladus, a satellite somewhat smaller than Ariel. On Enceladus, as on Ariel, there are both broad open regions and confined tectonic grabens that have undergone resurfacing by extrusion of material to the satellite's surface. However on Enceladus, despite Voyager images at least as good as those of Ariel, we see no hint that this resurfacing involved thick, convex flows. Instead, the material appears to have spread freely to form smooth, level surfaces. The surface gravity on Enceladus is lower than that on Ariel, so, other things being equal, flows with a given rheology should be thicker on Enceladus. Both these observations and theoretical considerations (*2*) indicate that a dominantly liquid material was erupted to the surface of Enceladus.

The style of resurfacing on Enceladus also is observed on all the other resurfaced saturnian satellites, which exhibit a wide range of thermal histories. Given this range, we have no reason to expect that the solid crystal fraction of liquids extruded to the surfaces of all the resurfaced uranian satellites should be consistently and substantially higher than those for all of the resurfaced saturnian satellites. In fact, since the NH_3-H_2O peritectic fluid suggested by Melosh and Janes is the same as that thought to have been erupted in the saturnian system, the melting temperature and solid crystal fractions should be similar in both cases. So, we have no reason to believe that if liquid were extruded to the surface of the uranian satellites it would behave very differently from the way it has in the saturnian system. For this reason, we favor solid over liquid resurfacing on Ariel and Miranda.

It is unfortunate that the Voyager images are not of sufficient resolution to allow us to distinguish between these two hypotheses on the basis of the morphologic details of the flows on the uranian satellites alone. However, our most important conclusion is that the uranian satellites contained exotic volatiles other than H_2O and that they underwent heating sufficient to mobilize these materials and to cause them to rise to the surface. Regardless of the resurfacing mechanism preferred on the basis of the ambiguous geologic evidence, this conclusion appears to be a robust one.

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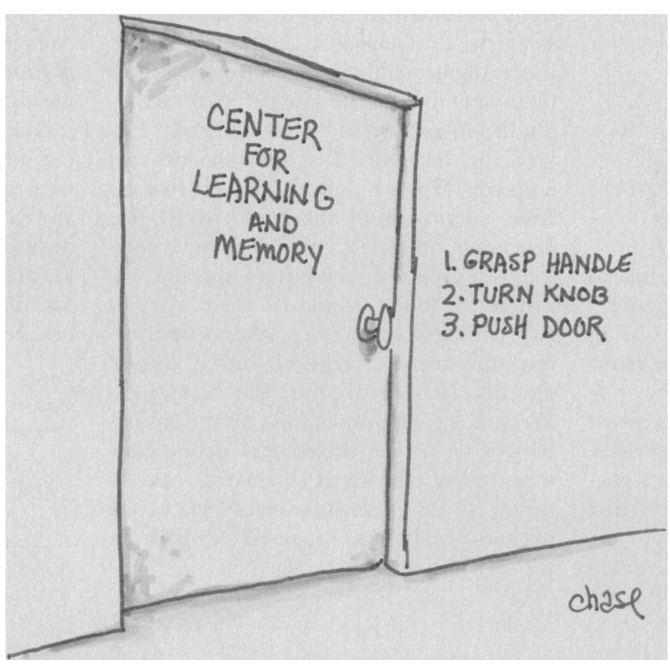

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