experiment with eukaryotic cellular DNA. For example, the phage recombinants we constructed were ligated at a PY DNA concentration of 66 μg/ml, and only one of the 20 clones studied contained a dimeric insert. If, for example, during the course of a shotgun experiment, tissue inadvertently infected with a papovavirus and containing virus or DNA at an average of 100 genome equivalents per cell was used as the source of DNA, the ligation reaction mixture containing 66 μg of cellular DNA would contain approximately 0.006 μg of viral DNA. Not only would the number of recombinants containing single copies of viral DNA be very low (about one clone per 10^4), but the number containing a dimeric insert would be negligible, since dimer formation would be highly concentration-dependent. Furthermore, our results and those of others (*7*) indicate that recombinants containing more than one copy of viral DNA are unstable in the rec^+ bacteria used for their propagation and would eventually disappear from the population.

In view of the widespread interest in the polyoma cloning experiments as a way of evaluating certain postulated potential biohazards of recombinant DNA research, it is important to give our perception of what the studies presented in this and the preceding report (*1*) do and what they do not contribute to the assessment of risk. First, no single experimental system or program can declare recombinant DNA research to be "dangerous" or "safe." Risk assessment of a large and complex area of research is incremental, and our findings should be viewed as a useful addition to, and confirmation of, the immense body of relevant preexisting knowledge of virology and bacteriology that has already been considered in the context of risk assessment.

Our data are most pertinent to the question of cloning viral sequences, but they have some implications for general cloning of eukaryotic DNA in *E. coli* as well. With regard to the former, our findings give no support to the concept, already virtually eliminated by the accumulating knowledge of the complexity of viral gene regulation and synthesis, that bacteria carrying recombinant plasmids or phages containing a eukaryotic viral genome would become producers of virus particles.

In the many discussions with virologists during the planning of these studies, there was a general consensus that the experiments would show *E. coli* carrying PY-λ or PY-plasmids to induce no PY infections when given by mouth, to give some infections when given parenterally, and to be quite infectious by parenteral injection if the insert was an oligomer. The most striking feature of our results, then, is the extremely low or absent infectivity of the recombinant molecules. In no instance was a recombinant molecule with a monomeric insert infectious, and in no instance did oral or parenteral administration of massive doses of live recombinant-containing *E. coli* induce PY infection.

We thus view these results as being highly reassuring with respect to the safety of cloning viral genomes in *E. coli*.

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References and Notes

1. M. A. Israel, H. W. Chan, W. P. Rowe, M. A. Martin, *Science* **203**, 883 (1979).
2. P. Leder, D. Tiemeier, L. Enquist, *ibid.* **196**, 175 (1977).
3. S. C. Hardies and R. D. Wells, *Proc. Natl. Acad. Sci. U.S.A.* **73**, 3117 (1976).
4. F. R. Blattner, B. G. Williams, A. E. Blechl, K. Denniston-Thompson, H. E. Farber, L. Furlong, D. J. Grunwald, D. O. Kiefer, D. D. Moore, J. W. Schumm, E. L. Sheldon, O. Smithies, *Science* **196**, 161 (1977).
5. L. V. Crawford, A. K. Robbins, P. M. Nicklin, K. Osborn, *Cold Spring Harbor Symp. Quant. Biol.* **39**, 219 (1974).
6. E. M. Southern, *J. Mol. Biol.* **98**, 503 (1975).
7. M. Perricaudet, A. Fritsch, U. Pettersson, L. Philipson, *Science* **196**, 208 (1977).
8. M. A. Israel, H. W. Chan, S. L. Hourihan, W. P. Rowe, M. A. Martin, *J. Virol.*, in press.
9. W. P. Rowe, J. W. Hartley, J. D. Estes, R. J. Huebner, *J. Exp. Med.* **109**, 379 (1959).
10. W. P. Rowe, R. J. Huebner, J. W. Hartley, in *Perspectives in Virology II*, M. Pollard, Ed. (Burgess, Minneapolis, 1961).
11. The studies described in this and the preceding report (*1*) were carried out under the containment conditions specified by the "NIH Guidelines for Research Involving Recombinant DNA Molecules" [*Fed. Regist.* **41**, 27902 (1976)]. All host vector systems were certified EK2 systems. All laboratory procedures involving viable bacteria or λ phage, including inoculations of mice, were done under P4 physical containment. Mice injected with free recombinant DNA molecules were held under P3 physical containment conditions. We thank Dr. L. Enquist for advice and help; Dr. J. Nutter and S. Nagle for the management of the P4 facility; and R. Boaze, J. Brewer, T. Bryan, J. Byrne, Dr. M. Collins, H. Grove, P. Howten, M. Meltzer, and H. Stull for technical assistance.

1 December 1978; revised 5 December 1978

Melting of Io by Tidal Dissipation

Abstract. *The dissipation of tidal energy in Jupiter's satellite Io is likely to have melted a major fraction of the mass. Consequences of a largely molten interior may be evident in pictures of Io's surface returned by Voyager I.*

The free eccentricity of Io's orbit is approximately .00001 (*1*). If this eccentricity accounted for all of the variation in the Jupiter-Io separation, the dissipation of energy from tides raised on Io by Jupiter would be negligibly small (*2*), since Io is synchronously rotating. But the resonant structure of the Galilean satellite leads to forced eccentricities that are considerably larger than the free values. Although still modest by most standards, these forced eccentricities coupled with the enormous tides induced by Jupiter lead to magnitudes of tidal dissipation that are certainly important and may completely dominate the thermal history of the innermost satellite Io. We will first establish values of the forced eccentricities and later substitute these into an expression for the total tidal dissipation.

The Galilean satellites are numbered in the conventional manner with 1 to 4 corresponding respectively to Io, Europa, Ganymede, and Callisto. Let λ_i, n_i $(= d\lambda_i/dt)$, and $\tilde{\omega}_i$ denote the mean longitude, mean orbital motion, and longitude of the perijove. The relation $n_1 - 3n_2 + 2n_3 = 0$ is satisfied exactly within observational error such that $\lambda_1 - 3\lambda_2 + 2\lambda_3 = 180°$ with no observed libration amplitude. This is the well-known Laplace relation and is often called simply the libration. In addition, the mean motions of 1 and 2 and, separately, of 2 and 3 are nearly in the ratio 2:1

$$n_1 - 2n_2 = n_2 - 2n_3 = 0^\circ.739507/\mathrm{day} \quad (1)$$

compared to $n_2 = 101^\circ.375$/day. The nearness of the two sets of mean motions to the 2:1 commensurability suggests that some of the resonance variables $\lambda_1 - 2\lambda_2 + \tilde{\omega}_1$, $\lambda_1 - 2\lambda_2 + \tilde{\omega}_2$, $\lambda_2 - 2\lambda_3 + \tilde{\omega}_2$, and $\lambda_2 - 2\lambda_3 + \tilde{\omega}_3$ may be librating about constant values. A periodic solution of the equations of motion with these resonance variables having constant values was used by de Sitter (*3*) as a first approximation in his theory of the Galilean satellites. Sinclair (*4*) has rederived the complete periodic solution and shown that in fact the first three of the four resonance variables are librating with small amplitude—the first and third about 0° and the second about 180°. This means that conjunctions of 1 and 2 occur when 1 is near its perijove and 2 is near its apojove; conjunctions of 2 and 3 oc-

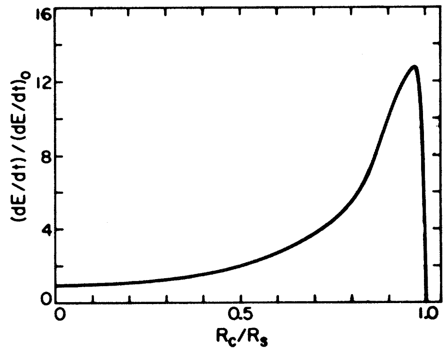

Fig. 1. Ratio of total tidal heating rate in a solid mantle to that in a completely solid Io as a function of the liquid core radius.

cur when 2 is near its perijove, but 3 may be anywhere in its orbit.

The librations of the above two-body resonance variables indicate that the Galilean system is very close to the periodic solution. Sinclair's derivation includes the values of the forced eccentricities, but we can arrive at the eccentricities of the two inner orbits from the opposite direction by using the fact that the first three of the above two-body resonance variables are librating about constant values. Therefore, on the average

$$n_1 - 2n_2 + \dot{\tilde{\omega}}_1 = n_1 - 2n_2 + \dot{\tilde{\omega}}_2 = n_2 - 2n_3 + \dot{\tilde{\omega}}_2 = 0 \qquad (2)$$

from which

$$\dot{\tilde{\omega}}_1 = \dot{\tilde{\omega}}_2 = -\,{}^{\circ}\!739507/\text{day} \qquad (3)$$

where the numerical value follows from Eq. 1. But

$$\dot{\tilde{\omega}}_1 = n_1\left[\frac{3}{2}\,\frac{R_J^2 J_2}{a_1^2} + \sum_{j=2}^{4} 2\,\frac{n_j^2}{n_1^2}\,\frac{m_j}{M}\left(\frac{a_j}{a_1}\right)^2 F_0(\alpha_{1j}) + \frac{m_2}{M}\,\frac{a_1}{a_2 e_1} F_1(\alpha_{12}) \cos(\lambda_1 - 2\lambda_2 + \tilde{\omega}_1)\right] \qquad (4)$$

describes the motion of Io's perijove, where R_J is Jupiter's equatorial radius; J_2 is the zonal gravitational harmonic; m_j and M are masses of satellites and Jupiter; $\alpha_{1j} = a_1/a_j$, where a_i are the semimajor axes of the orbits; and $F_0(\alpha_{ij})$ and $F_1(\alpha_{ij})$ are 0(1). The first term is due to Jupiter's oblateness, the terms in the sum are the secular perturbations of the other satellites, and the last term is a periodic term which is now constant because of the resonance. All quantities in Eq. 4 are known except the eccentricity e_1 and the solution yields

$$e_1 = .0043 \qquad (5)$$

for Io. A similar equation gives

$$e_2 = .011 \qquad (6)$$

for Europa. Both agree with Sinclair's values. Lieske (*5*) finds the "eccentricity-like" term with argument $2\lambda_1 - 2\lambda_2 (= \lambda_1 - \tilde{\omega}_1)$ and amplitude .0041 in his precise expression for the jovicentric distance of Io, in good agreement with the above value of e_1.

The total tidal dissipation in a synchronously rotating, homogeneous satellite in an eccentric orbit is given by Peale and Cassen (*2*)

$$\frac{dE}{dt} = \frac{36}{19}\,\frac{\pi\rho^2 n^5 R_s^7 e^2}{\mu Q} \qquad (7)$$

where ρ is the density, μ is the rigidity, R_s is the satellite radius, and Q is the specific dissipation function. In Eq. 7 terms proportional to e^3 and smaller have been neglected. From their densities ($\sim$3.5 g/cm^3) Io and Europa are each likely to have a rigidity similar to that of the moon, $\mu = 6.5 \times 10^{11}$ dyne/cm^2. We find

$$\left.\frac{dE}{dt}\right|_1 = \frac{1.6 \times 10^{21}}{Q_1}\ \text{erg/sec}$$

$$\left.\frac{dE}{dt}\right|_2 = \frac{7.8 \times 10^{19}}{Q_2}\ \text{erg/sec}$$

The energy dissipated in, say, the satellite Io must come from the orbit, which would lead to an increase in the orbital mean motion

$$\frac{dn_1}{dt} = \frac{3}{n_1 m_1 a_1^2}\,\frac{dE_1}{dt} = \frac{7.4 \times 10^{-22}}{Q_1}\ \text{rad/sec}^2 \qquad (8)$$

For comparison, the tidal transfer of energy to the orbit from Jupiter's rotation is

$$\left.\frac{dn_1}{dt}\right|_J = -\frac{9}{2}\,k_2\,\frac{m_1}{M}\,\frac{n_1^2}{Q_J}\left(\frac{R_J}{a_1}\right)^5 = -\frac{2.5 \times 10^{-17}}{Q_J} \qquad (9)$$

where $k_2 = 0.5$ is the fluid Love number for Jupiter. If these rates are to exactly cancel

$$Q_J = 3.4 \times 10^4\, Q_1 \qquad (10)$$

For reasonable values of Q_1 (such as 100) the above Q_J exceeds the lower bound of $\sim$50,000 derived from the current proximity of Io to Jupiter after 4.6×10^9 years of tidal evolution (*6*). It is seen that the orbit configuration might be maintained while the energy dissipated in Io is ultimately replenished from Jupiter's rotation. Dissipation in Io would also tend to reduce the eccentricity, but this is prevented by the resonant interaction with Europa.

The current tidal heating rate in a homogeneous Io (with $Q = 100$) is about three times the current radioactive heating rate estimated for the moon (*7*). The energy would be dissipated nonuniformly, with a central heating rate about three times the average, or 2×10^{-6} erg/cm^3-sec. Earth's moon is nearly the same size and mass as Io but is heated by the decay of radioactive isotopes at an average rate of 2.3×10^{-7} erg/cm^3-sec (*7*). Thus, the center of a homogeneous Io would be heated at a rate nearly ten times that inferred for the lunar interior, and this factor would be further enhanced by any radioactive heat sources within Io, or if the lunar heat sources were substantially concentrated toward the surface. Since the moon is believed to be near or at the melting point in its deep interior (*8*), it seems likely that the much higher heating rate in Io has caused melting in Io's interior.

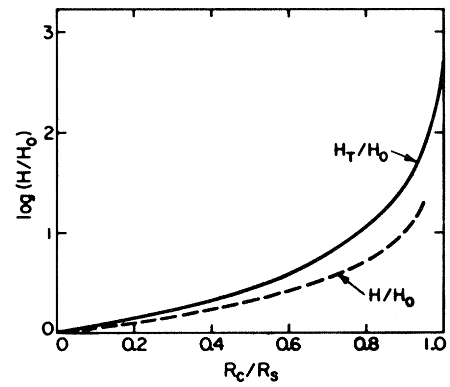

Fig. 2. (Solid curve) Normalized average local dissipation in a solid mantle overlying a liquid core as a function of the normalized core radius. (Dashed curve) Normalized heating rate necessary to maintain a given temperature across a solid convecting mantle.

But the heating rate due to tidal dissipation in the solid mantle of a planet with a liquid core can be much greater than that in a homogeneous body with properties like those of the solid mantle. In Fig. 1 we show how the total heating rate varies as a function of a liquid core radius as determined by the calculations of Peale and Cassen (*2*). The increase in dissipation rate is due to the increased amplitude of the strain variation as the mantle thickness decreases. The sharp increase in total dissipation with core radius can lead to the runaway melting described by Peale and Cassen (*2*). Heating in the solid mantle melts material near the liquid core, thereby diminishing the mantle thickness. The thinner elastic shell undergoes greater deformation and hence a greater heating rate.

However, before we can conclude that such a runaway melting is likely for Io, the efficiency with which heat is removed from the interior must be estimated. It is likely that heat generated within a solid planetary body as large as Io is transported by solid-state convection. The uniform heating rate that would be necessary to maintain a temperature difference ΔT across a solid convecting layer of mantle can be estimated by the relation $H = (0.4)\Delta T k R_{a}^{1/4}/L^2$. Here L is the mantle thickness, k is the thermal conductivity, and R_a is the Rayleigh number $\alpha g L^5 H/2k\kappa\nu$ (g, α, κ, and ν are the gravitational acceleration thermal expansion coefficient, thermal diffusivity, and kinematic viscosity, respectively). This formula is based on both experimental data (*9*) and numerical calculations with spherical geometry (*10*). Its application to problems of planetary heat transfer is discussed in detail by Schubert *et al.* (*11*).

Suppose that, for $L = R_s$ (no liquid core) and ΔT equal to that necessary for melting at the center of the satellite, H was just equal to H_0, the mean tidal heating rate for a solid Io. Then H/H_0 is approximately R_s/L for all L, since ΔT and the other parameters would not vary appreciably with L. Figure 2 shows $H/H_0 = R_s/L$. Also plotted in Fig. 2 is H_T, the mean tidal dissipation rate in the mantle, also normalized by H_0. As the core radius increases, heating due to tidal dissipation exceeds by an increasing amount the energy that can be removed by solid-state convection. By comparison with the moon, it seems likely that $H/H_0 < 1$ for $L = R_s$, in which case the dashed curve in Fig. 2 would lie even farther below the curve of H_T/H_0. Thus, solid convection cannot prevent the melting from rapidly spreading through the rest of the satellite once melting has occurred at the center.

The result of this runaway melting process is a planet with a large molten core and a solid outer shell, the thickness of which is limited by conduction of the internally generated heat to the surface, or possibly by the onset of nonelastic behavior such as fracture. Conduction-limited runaway would result in a thin shell indeed. The solid curve in Fig. 2 reaches an upper limit of 500, which was calculated by using the shell equations derived by Peale and Cassen (*2*). Then for conductive equilibrium of the shell, $H/H_0 = 2k\Delta T/H_0 L^2$. With $k = 4 \times 10^5$ erg/cm-sec-K and $\Delta T = 1300$ K, the thickness L would be 18 km. The periodic component of the tide in this nearly fluid satellite would have a maximum amplitude of 100 m.

The implications of the orbital resonances of the inner three Galilean satellites are profound for the thermal state of Io. These calculations suggest that Io might currently be the most intensely heated terrestrial-type body in the solar system. The surface of the type of body postulated here has not yet been directly observed, and although the morphology of such a surface cannot be predicted in any detail, one might speculate that widespread and recurrent surface volcanism would occur, leading to extensive differentiation and outgassing (*12*). Transient infrared brightening of Io has recently been observed (*13*). Surface magmatic events might produce such brightening. The appearance of craters produced by events of sufficient energy to penetrate the crust should be different from those on bodies with thick, solid mantles. The question of distinguishing between a solid mantle and a liquid mantle with a thin crust is important for the outer icy satellites as well as for Io. Although this structural model of Io is analogous to the solid crust-liquid mantle model proposed for the large icy satellites (*14*), it has recently been shown that the hypothetical liquid mantle of these satellites would be solidified by solid-state convection in the icy crust (*15*). Finally, cosmic elemental abundance ratios, the density of Io, and the high internal temperatures would imply a molten iron core with a radius perhaps one-third that of Io. Therefore, by analogy with Earth, the satellite might have a magentic field, the interaction of which with the jovian magnetosphere would be the source of interesting plasma phenomena. Voyager images of Io may reveal evidence for a planetary structure and history dramatically different from any previously observed.

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References and Notes

1. W. de Sitter, *Ann. Leiden Obs.* **16**, part 2 (1928).
2. S. J. Peale and P. Cassen, *Icarus* **36**, 240 (1978).
3. W. de Sitter, *Mon. Not. R. Astron. Soc.* **91**, 706 (1931).
4. A. Sinclair, *ibid.* **171**, 59 (1975).
5. J. Lieske, private communication.
6. P. Goldreich and S. Soter, *Icarus* **5**, 375 (1966).
7. P. Cassen, R. T. Reynolds, F. Graziani, A. Summers, J. McNellis, L. Blalock, *Phys. Earth Planet. Inter.*, in press.
8. Y. Nakamura, G. V. Latham, H. J. Dorman, F. K. Duennebier, *Proc. 7th Lunar Sci. Conf.* (1976), p. 3113.
9. F. A. Kulacki and A. A. Emara, *J. Fluid Mech.* **83**, 375 (1977).
10. R. E. Young, *ibid.* **63**, 695 (1974).
11. G. Schubert, P. Cassen, R. E. Young, *Icarus*, in press.
12. F. P. Fanale, T. V. Johnson, D. L. Matson, in *Planetary Satellites*, J. A. Burns, Ed. (Univ. of Arizona Press, Tucson, 1977).
13. F. C. Witteborn, J. D. Bregman, J. B. Pollack, *Science* **203**, 643 (1979).
14. J. Lewis, *ibid.* **172**, 1127 (1971).
15. R. T. Reynolds and P. Cassen, *J. Geophys. Res. Lett.* in press.
16. We gratefully acknowledge discussions with R. Greenberg and J. Lieske and thank the latter for kindly furnishing a computer printout of his calculations of the Galilean satellite motions. S.J.P. is supported in this research by NASA grant NGR 05-010-062 and by NASA-Ames Research Center under interchange NCA-2-OR680-701.

26 January 1979

Anomalous Bottom Water South of the Grand Banks Suggests Turbidity Current Activity

Abstract. *Highly turbid bottom water at the margin of the Sohm Abyssal Plain was identified by its temperature, salinity, and oxygen content as originating upslope on the continental rise. The fact that the particulate concentrations were one to two orders of magnitude higher than are normally found in deep ocean waters suggests a turbidity current as the agent bringing this water downslope.*

In 1952 Heezen and Ewing (*1*) showed that submarine telegraph cables must have been severed by a massive turbidity current that developed after the 1929 Grand Banks earthquake rather than as the result of the direct action of earth shocks, as had been supposed. Although it is doubtful that turbid water remains from that particular event, muddy water has been photographed at the bottom in the Sohm Abyssal Plain, presumably from more recent turbidity current events in the same region (*2*).

Near-bottom water samples collected south of the Grand Banks in 1971 contained an unusually high concentration of suspended particulate matter. Many hundreds of light-scattering profiles have been obtained in Atlantic Ocean waters, and the broad-scale horizontal and vertical distribution of particulate matter has been mapped from these data (*3*). Our 1971 measurements are truly anomalous when compared to this overall distribution, and in light of some recent data collected in the same region (*4-7*) we report here on our reexamination of the 1971 data.

The bottom waters overlying the western margins of the North and South Atlantic basins contain high concentrations of suspended particulate material. Con-