be observed and may spend substantial portions of their lives at depths other than those at which they secrete their tests.

Finally, in the case of *Sphaeroidinella dehiscens*, we recognize that our results depend on the visual estimation of crust (cortex) and inner material (spinose *sacculifer*). We cannot deny that the cortex includes some spinal growth. For the sample from the Atlantic Ocean (C-1) we estimate that the cortex contained less than 50 percent inner material since the cortex was relatively thick and its exterior was not perforated by spinal growth. Even if we assume that in the crustal material we analyzed the cortex was contaminated by the presence of up to 50 percent spinose material we find the depth of secretion of the cortex would be no greater than 140 m. The calculated depth is considerably shallower than the depths of greater than 300 m previously suggested by Bé and Hemleben (*5*).

We have not suggested that isotopic data could prove whether or not *S. dehiscens* is encrusted *G. sacculifer*, but we maintain that the isotopic data do set limits on the depths at which test formation has occurred.

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6 May 1971

How Did Venus Lose Its Angular Momentum?

Singer's proposed mechanism (*1*) for reducing a higher primordial angular momentum of Venus to its present value has one unfortunate side effect: it may destroy the planet in the process. Singer suggests that the angular momentum was reduced by tidal interactions with a captured moonlike body, which then disappeared by crashing into Venus. He writes (*1*, p. 1198).

> The moon is fated to crash into the planet's surface and will presumably disappear. Yet a "smile of the Cheshire cat" may remain. . . . Should events have taken place in this manner, then capture of a moon may have provided the trigger for the internal melting of Venus, for the formation of a core, and for the copious production of an atmosphere through volcanic emissions. . . .

The mass calculated for this hypothetical moon is about twice that of the earth's moon (*1*, p. 1198), and the disposal of this body thus involves a hypervelocity collision between a satellite that is about 30 percent larger in diameter than our moon and a primary that is about 5 percent smaller than the earth. A brief consideration of the kinetic energy involved in such an impact suggests that the effects of such a collision will be much stronger than Singer has implied and might even involve significant fragmentation of Venus itself.

The kinetic energy of impact is:

$$E = \tfrac{1}{2}\, m\, v^2 \qquad (1)$$

where m is the mass of the moon and v is the impact velocity. The calculated mass of the moon is 1.46×10^{26} g (*1*, p. 1198). A minimum value for the impact velocity is given by the circular velocity v_c at the surface of Venus, which may be calculated from the relation

$$v_c = (Rg)^{1/2} \qquad (2)$$

where R is the radius of Venus (6.06×10^8 cm) and g is the surface acceleration of gravity (877 cm $\sec^{-2}$) (*2*, pp. 49, 673). The minimum impact velocity of the moon onto the surface of Venus is thus

$$v = v_c = 7.29 \text{ km/sec}$$

The minimum kinetic energy of the impact is thus

$$E = \tfrac{1}{2}\, m\, v_c^2 = 3.9 \times 10^{37} \text{ ergs} \qquad (3)$$

The specific kinetic energy per gram of target mass, E/M, is thus 8.0×10^9 erg/g. [The mass of Venus, M, is 4.87×10^{27} g (*2*, p. 673).]

Complete destruction of the hypothetical moon requires that the impact with the surface of Venus occur at an angle that is large enough so that ricochet and spallation of the projectile are not significant. For this case, by using the value for the kinetic energy of impact, it is possible to estimate the diameter (D) of the resulting crater by using scaling laws (*3–5*) of the form

$$E/E_0 = (D/D_0)^n \qquad (4)$$

where E_0 and D_0 are the energy and diameter, respectively, of a reference crater and n is usually between 3 and 4. I use Meteor Crater, Arizona, as a standard for which $E_0 = 7.11 \times 10^{22}$ ergs and $D_0 = 1.189$ km (*4*). The case where $n = 4$ (gravitational scaling) (*5*) sets a probable minimum diameter; for $n = 4$, $D = 5760$ km. For $n = 3$ (cube root scaling), a probable maximum diameter is $D = 97{,}400$ km. Since the diameter of Venus is only 12,120 km (*1*, p. 1198; *2*, p. 673), it is not clear that the planet could contain the crater produced by the proposed impact.

It can be argued that such scaling laws, developed for relatively small craters, cannot be meaningfully applied to such a catastrophic event. However, more general considerations of the mechanics of hypervelocity impact cratering (*4, 6*) lead to the same conclusions. In such events, the diameter of the resulting crater is generally from 10 to 30 times the diameter of the projectile, and the projectile itself generally penetrates the target for distances of two to five times its own diameter during crater formation.

The diameter of the hypothetical moon can be calculated from the relation

$$m = 4/3\, \pi\, r^3 \rho \qquad (5)$$

If a density of $\rho = 3.34$ g/cm^3, equal to that of our moon, is used, the calculated diameter is 4370 km. (The exact density is not critical, since a change of a factor of 2 in density produces only about a 30 percent change in diameter.) Substitution of this diameter into the general cratering relations discussed above also indicates the production of an impossibly large and deep crater relative to the size of Venus itself.

Severe alteration of Venus by the impact is also indicated simply by the large kinetic energy involved. The specific kinetic energy of impact per gram of target mass (Venus) is 8.0×10^9 erg/g, nearly three orders of magnitude greater than that required for complete fragmentation of small bodies in hypervelocity impact experiments at low impact velocities (7) and comparable to the amount needed to completely melt most silicate rocks (1, p. 1198).

Finally, one can compare the kinetic energy of impact with the total gravitational potential energy of Venus itself. The latter can be calculated from the relation

$$\Omega = 3/(5-n)\ (GM^2/R) \qquad (6)$$

For the case $n = 0$ (8, pp. 230–231), $\Omega = 1.6 \times 10^{39}$ ergs. The kinetic energy of the proposed collision is thus theoretically sufficient to disperse about 3 percent of the mass of Venus to infinity.

Even if Venus could survive this proposed collision substantially intact, such a concentrated release of kinetic energy would produce widespread melting, vaporization, deep fracturing, and possible temporary fragmentation and dispersal. Far from merely acting as a "trigger" for internal processes (1, p. 1198), the direct effects of this impact would probably dominate the entire early history of the planet. Singer's method for changing the angular momentum of Venus may be plausible, but the aftereffects are more suggestive of Humpty Dumpty (9, p. 262) than of the Cheshire cat.

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12 January 1971

French's objections apply to a moon M_I which *impacts* directly upon the surface of Venus. They do not apply to my case (1) where the moon M_C is first *captured* into an orbit, retrograde with respect to Venus; hence, my conclusions are strengthened since capture is less likely than direct impact.

A moon that impacts directly, presumably with a velocity just above that of escape (10.3 km/sec) would certainly produce a change in the planet's angular momentum. But in order to reduce it to zero, the moon M_I would have to be quite massive compared with M_C: first, because the "moment arm" is reduced to about one-half; and, secondly, because much of the mass of M_I would ricochet away or spall off upon impact, carrying away much of the angular momentum and kinetic energy. Even if the latter did not happen, much kinetic energy would go into the explosion in the crater center where hot gas is created. A very small amount of the planet might be lost, but self-gravitation would keep it from dispersing. (French's detailed discussion really shows that scaling upward from small craters in flat, semi-infinite surfaces loses validity when the crater size is of planetary dimension.)

A captured moon changes from a near-parabolic orbit to a nearly circular orbit under the influence of tidal friction (2); if initially retrograde, it remains retrograde and shrinks down upon the planet. Once inside the Roche limit (about 2½ planetary radii), however, the moon breaks into pieces under the influence of the tidal distending forces. The time scale of orbit evolution is thereby slowed and is determined now by the mass of each individual fragment (except for resonances). The effect will be a series of impacts by small bodies, which are dispersed both in time and space. The impacts will occur in a latitude belt around the planet's equator; the width of the belt depends on the initial inclination of the moon.

The classical Roche limit applies to two uniform deformable bodies of mass M and m, respectively, and density ρ_M and ρ_m, revolving around their common center of gravity with angular velocity ω. Their separation is given by D. When $m/M \rightarrow 0$, and M is a rigid body, the Roche limit distance is given (3) by

$$D_{\min} = 2.4554\ (\rho_M/\rho_m)^{1/3} R_M \qquad (1)$$

where R_M is the radius of body M.

The numerical coefficient in Eq. 1 is dependent on the assumptions made in the discussion and is also influenced by the mechanical cohesion of the body m. For example, let us divide m into two equal masses m' separated by a small distance $2d$, which are revolving about each other with the same angular velocity ω given by

$$\omega^2 = G\ M/D^3 \qquad (2)$$

where G is the gravitational constant. Then the "inner" mass will experience a net force

$$F_1 = \omega^2\ (D-d)\ m' - GM\ m'\ (D-d)^{-2} \qquad (3)$$

and the outer mass a net force

$$F_2 = \omega^2\ (D+d)\ m' - GM\ m'\ (D+d)^{-2} \qquad (4)$$

The resultant force tending to separate the two masses is

$$F = F_1 - F_2 = 3\ GM\ D^{-3}\ (2d)m' \quad (5)$$

Hence the distance for two finite-sized bodies in contact, beyond which the mutual gravitational attraction is larger than F, is

$$D_{\min} = (24\ \rho_M/\rho_m)^{1/3} R_M \qquad (6)$$

Note that the coefficient $24^{1/3} = 2.88$ will be reduced if cohesion is considered.

The final result is as follows. Typically about 50 percent of the moon's initial (negative) angular momentum is transmitted to the planet through (solid-body) tidal interactions *before* any impacts occur; the fact that the moon has split into fragments lengthens the time scale but does not affect this result. The remainder of the angular momentum is transmitted through the impacts, except for some loss by ricocheting. We see, therefore, that about three-fourths of the planet's kinetic energy of rotation is dissipated internally, before any impacts occur, so that a thick planetary atmosphere may well have evolved by internal melting and volcanism before the impacts are completed. This atmosphere, in turn, reduces ricocheting and therefore increases the angular momentum transfer from moon to planet to nearly 100 percent.

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