PLANETARY COLLISION CALCULATIONS: ORIGIN OF MERCURY

A. G. W. Cameron and W. Benz*, Harvard-Smithsonian Center for Astrophysics, and W. L. Slattery, Los Alamos National Laboratory.

The observed mean density of the planet Mercury of 5.44 g/cm^3 (uncompressed ~5.3 g/cm^3) implies an iron to silicate mass ratio in the range from 66:34 to 70:30, about twice that of any of the other terrestrial planets, the Moon, and the Eucrite Parent Body [1]. The mean density of the Earth is 5.52 g/cm^3, corresponding to an uncompressed density of ~4.45 g/cm^3. We have explored a scenario for producing this high mean density which involves a major planetary collision that blows off the bulk of the silicate mantle from the original Mercury protoplanet [2,3].

The scenario in which this collision may have played a role in producing the strange density of Mercury is that of planetary accumulation from planetesimals. After turbulence dies away in the primitive solar nebula, small solid bodies, presumably in the form of clumps of interstellar grains, are able to settle to midplane, where they are likely to become gravitationally unstable to the formation of planetesimals of asteroidal size (a few kilometers in radius) [4]. There follows an accumulation of these planetesimals into bodies of increasing size [5]. This accumulation tends to produce a largest body in a given "feeding zone", with the next largest body less in mass by a factor of a few, and so on down from there.

Toward the end of the accumulation process the second largest body is likely to collide with the largest, with potentially surviving observable effects. In the case of the Earth this is the collision that may have initiated the formation of the Moon [6]. For Mercury we have carried out smoothed particle hydrodynamic collisional calculations using essentially the same code used in [6]. We have assumed that the "target" protoplanet Mercury was 2.25 times the mass of the present Mercury, in order to give it approximately a chondritic silicate to iron ratio, and we have hit it with a "projectile" of one-sixth that mass at rather higher velocities.

In [6] (see also the accompanying abstract at this meeting by the same authors) the Tillotson equation of state was used, in which rocky material was represented by granite. Beyond our Mercury run 7 the ANEOS equation of state was used which was developed at the Sandia Laboratories. This equation of state has a better representation of mixed phase conditions, when both a vapor phase and a condensed matter phase are present at the same time. For rocky material we used dunite with this equation of state; the appropriate equation of state parameters for this material were determined by Jay Melosh, and we are grateful to him for providing them to us.

In our early runs we used rock plus an iron core for the target but just rock for the projectile. After run 4 the projectile had an iron core as well. In these runs the protomercury target was represented by 3000 particles, of which 959 were iron and 2041 were silicate rock. The projectile of one-sixth the mass was represented by 1000 particles, each half the mass of the particles used in the target. In the projectile 319 of the particles were iron (beyond run 4) and 681 were rock.

The results of the collision calculations are shown in the Table. In run 3 the projectile had an impact velocity of 27 km/s at infinity; it hit the target centrally and knocked off most of the silicate rock and some of the iron. This would be a very good candidate for the kind of collision that would produce the observed Mercury, except that the composition of the projectile is unrealistic. In run 4 the velocity of the impactor was increased to 38 km/s, resulting in the complete disruption of the target.

With run 5 we started a realistic series of cases by putting an iron core into the projectile. We chose an impact velocity of 25 km/s and found that the target was once again totally disintegrated. It was thus evident that the denser core in this impactor enabled the target to be disintegrated at a significantly lower velocity than was true of the softer case in which the impactor was just rock. In run 6 the velocity was lowered to 20 km/s and the target survived the collision, after once again losing nearly all its silicates. It is interesting to note, however, that the iron core in the target lost 43.9% of its mass but picked up 37.7% of the mass of the iron core in the projectile. This is an excellent candidate to be the scenario for the formation of Mercury. However, in run 7, with an impact velocity of 15 km/s, the collision leaves more than the present mass of Mercury, and hence this is not a good candidate for the Mercury scenario, especially since some of the lost mass will be reaccumulated.

Starting with run 8 we used the ANEOS equation of state. Run 8 was essentially a repeat of the conditions in run 6. The results of these two runs were very similar, showing that the results do not depend sensitively on the the character of the equation of state and the choice of rocky material. The amount of iron left in the residual body is nearly the same; there is a little less iron from the target and a little more from the projectile. The total mass left behind after the collision is nearly the same in the two cases, and is a satisfactory value of only about 60% of the present mass of Mercury.

Runs 9 and 10 were head-on collisions like run 8, but at progressively lower collision velocities, 15 km/s for run 9 and 10 km/s for run 10. The amount of mass ejected in the collision decreases with decreasing collision velocity, so that in the 10 km/s case the planet is left with more mass than it had at the beginning. Neither of these cases is a candidate to produce the current Mercury.

Runs 11 and above were cases in which the projectile hit the target off-center, with impact parameters just over half the radius of the target. The striking characteristic of these runs is that the off-center collision is much less effective in ejecting mass from the target. Whereas a central collision at 20 km/s leaves only 0.60 Mercury masses,

* Also Los Alamos National Laboratory and Geneva Observatory

PLANETARY COLLISIONS: MERCURY

Cameron, A. G. W., Benz, W., and Slattery, W. L.

a similar collision which is non-central leaves 1.76 Mercury masses, too high to make this a candidate collision for the present Mercury. Only in run 14, where the impact velocity was 35 km/s, does the planetary remnant become reduced to 0.59 Mercury masses, which makes it a good candidate for forming the observed planet.

As discussed in the introduction, the present silicate/iron ratio in Mercury is about in the range 0.4–0.5, and this should be regarded as equal to or more than the value to be expected in the remnant produced in these calculations for the result to be considered a candidate collision to lead to the present Mercury. As may be seen in the Table, only the central collisions near 20 km/s and the non-central collisions near 35 km/s satisfy this criterion.

TABLE. The outcome of the Mercury collision scenarios. The impact parameter is in units of the target radius. The values given for target and projectile iron and silicate are the percentages of the numbers of particles in the residual body coming from these four sources. The mass ratio is the residual mass relative to the present mass of the planet Mercury (3.3×10^{26} gm).

Case	Vel. km/s	Impact Param.	Targ. Iron	Proj. Iron	Targ. Sil.	Proj. Sil.	Sil./Iron Ratio	Mass Ratio
3	27	0.00	76.5%		5.1%	0.4%	0.14	0.67
4	38	0.00	Disintegrated					
Below here the impactor had an iron core								
5	25	0.00	Disintegrated					
6	20	0.00	56.1%	37.7%	5.9%	7.5%	0.25	0.58
7	15	0.00	93.1%	7.2%	22.0%	2.8%	0.51	1.18
Below here the ANEOS equation of state was used								
8	20	0.00	48.8%	42.0%	8.8%	11.3%	0.41	0.60
9	15	0.00	86.2%	69.3%	42.1%	31.3%	1.03	1.67
10	10	0.00	99.2%	97.8%	79.1%	58.6%	1.64	2.65
11	15	0.66	99.4%	0.6%	70.3%	12.3%	1.55	2.33
12	20	0.55	94.3%	3.8%	47.1%	6.8%	1.08	1.76
13	28	0.55	80.0%	0.0%	20.0%	1.2%	0.54	1.03
14	35	0.55	57.0%	0.3%	7.8%	0.3%	0.29	0.59

In the course of a typical collision a great deal of material is thrown out from the site of the collision, some to escape and the rest to fall back onto the planet. Much of this material is clumped into clusters of particles and the rest consists of single particles. These single particles are likely to have passed through the vapor phase and many of them will have recondensed upon expansion. At the end of the Cray runs this is the typical situation: a cloud of material surrounding a planetary core, some of it rising and the rest falling back. From our post-Cray analyses of the results we find that nearly all of the larger clumps of particles (which tend to be iron-rich) fall back onto the planet and nearly all of the single particles escape. In the cases where the planet is disintegrated, this clumpy situation still exists, but the largest clumps are only of moderate size and very few of them collide with one another.

It is evident that a "successful" collision should be judged to be one in which the mass of the protoplanet is reduced well below that of the present planet Mercury and in which the remnant is composed predominantly of iron. All of the material which is ejected in the collision goes into independent orbit around the Sun; these orbits must necessarily cross the orbit of the remaining protoplanet. The present orbital elements of Mercury are subject to secular variation with time due to other planetary perturbations, so we do not know what the orbit of the remnant would have been. Nevertheless, we took the present orbit of Mercury as a suitable prototype of that orbit, and calculated whether any of the particles ejected from the collision would have been put into orbits that would cross the orbit of Venus. We found that in general only a few of the particles would do so if ejected at aphelion, and usually a few dozen and at most a few hundred would do so at perihelion. Thus only a minority of the particles can be removed from Mercury-crossing orbits by other planetary perturbations.

The key to this situation probably lies in the fact that most of the ejected material has passed through the vapor phase. Upon expansion, this material will cool and condense into solid particles, but if the vapor is by that time at fairly low density, then the particle sizes will probably be very small, in the sub-centimeter size range. Such small particles will be drawn into the Sun by the Poynting-Robertson effect in a time short compared to their expected collision time with Mercury of about 10^6 years. The larger chunks ejected from the collision are much too large to be affected by the Poynting-Robertson effect, and these are likely to be reaccumulated upon Mercury.

It must not be forgotten that Mercury will also accumulate additional material which is perturbed into the inner solar system for a considerable period of time after the collision hypothesized here. This will add an unknown amount of mass to that reaccumulated from the collision.

[1] Basaltic Volcanism Study Project, 1981, *Basaltic Volcanism on the Terrestrial Planets*, Pergamon, N. Y. [2] Smith, J. V. 1979, *Mineral. Mag.* 43:1–89. [3] Wetherill, G. 1985, Remark at Lunar and Planetary Science Conference, Houston. [4] Goldreich, P., and W. Ward 1973, *Astrophys. J.* 183:1051–1061. [5] Wetherill, G. 1980, *Ann. Rev. Astron. Astrophys.* 18:77–113. [6] Benz, W., W. L. Slattery, and A. G. W. Cameron 1986, *Icarus* 66:515–535.