THERMAL EVAPORATION OF GIANT GASEOUS PROTOPLANETS; A.G.W. Cameron, Harvard–Smithsonian Center for Astrophysics, Cambridge, MA 02138; W.M. DeCampli, California Institute for Technology, Pasadena, CA 91125; and P.H. Bodenheimer, Lick Observatory, University of California, Santa Cruz, CA 95064.

We report here the results of further numerical experiments on the evolution of giant gaseous protoplanets subjected to a variety of external boundary conditions. In particular, to the extent that giant gaseous protoplanets in the inner portions of the primitive solar nebula can be regarded as primarily embedded in a thermal bath, we conclude that such objects will undergo thermal evaporation. The role played by these protoplanets in the formation of the terrestrial planets will depend on the competition between precipitation of dust grains and clumps through gas and the expansion and loss of the gas.

We expect giant gaseous protoplanets to be formed as a result of gravitational instabilities in the primitive solar nebula (1). Such instabilities may be initially axisymmetric in character, with the rings then fragmenting into individual blobs, some of which will merge upon collision. In isolation, these protoplanets would then evolve much in the manner of stars, with about half of the internal energy released by gravitational contraction being convected to the surface and radiated into space, until the central temperature becomes high enough to dissociate hydrogen molecules, at which point the protoplanet goes into dynamical collapse. The calculations of DeCampli and Cameron defined the internal thermodynamics of the evolutionary paths of the protoplanets, assuming that the masses of the protoplanets did not change as a function of time (2). However, the time scales and the actual evolutionary behavior depend on the surface boundary conditions applied to the protoplanet by the primitive solar nebula.

At the Eleventh Lunar and Planetary Conference (3) we reported the results of some numerical experiments designed to obtain some preliminary insight into the effect of such boundary conditions. The external boundary conditions imposed with a specified time variation included thermal baths and surface boundary pressures representing gas with entropies both higher and lower than possessed by the gas in the outer envelope of the protoplanet. These protoplanets included objects with masses in the Jupiter and Saturn mass ranges.

Most of these experiments were successful only for the less severe imposed boundary conditions which we identified with conditions likely to exist in the Jupiter region of the primitive solar nebula. For conditions more typical of the inner solar nebula, the region of the terrestrial planets, where the boundary conditions varied more rapidly over a wider range, our evolutionary calculations became unstable and blew up.

The problem was tracked down to a condition contained in the evolutionary code designed to handle accretion shocks at the surface of a collapsed protoplanet, which was incompatible with more rapidly varying imposed surface boundary conditions. When this condition was removed, we had no problem following the evolution of giant gaseous protoplanets subjected to boundary conditions thought to be typical of the inner solar nebula.

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With this change in the code, we repeated our earlier calculations and verified that our previous conclusions remained correct. Briefly, these are:

1. The imposition of a pure thermal bath of continually rising temperature causes the expansion of the outer envelope and presumably the gradual thermal evaporation of the protoplanet.

2. The imposition of a pressure and temperature boundary condition at the surface with a time history like that of the solar nebula but a higher adiabat than the envelope material retards the flow of energy to the surface until the pressure is released, at which point the evolution of the protoplanet resumes and approaches its normal path.

3. If, instead, the boundary pressure and temperature represent a lower adiabat than the envelope gas, then the evolution of the protoplanet is accelerated.

We verified that the second and third conclusions held also for time variations and pressure variations of the general character to be expected in the inner solar nebula.

A real giant gaseous protoplanet embedded in the primitive solar nebula will have a continuous gas interface with the nebula in the equatorial region, across which energy, angular momentum, and mass can flow. It will form its own boundary radiating into space in the polar regions. Hence the behavior of a protoplanet in a thermal bath is a particularly interesting clue to the behavior of the protoplanetary polar regions during the evolution of the primitive solar nebula. On the other hand, it appears that the imposed pressure boundary conditions on the equatorial plane of the protoplanet will have much more complex effects than implied by the above results, which pertain to the unrealistic assumption of spherically symmetrically imposed boundary pressure conditions.

If the entropy in the nebula is lower than in the protoplanet envelope in the equatorial plane, then gas exchange will eliminate the negative entropy gradient, although some time may be required for this because diffusion across the angular momentum barrier is needed. If the external entropy is higher than in the envelope, then for equal pressure conditions the external gas will be hotter, and energy will flow into the envelope in the equatorial plane. It is precisely in these conditions that energy is likely to be flowing into the polar regions due to the presence of a thermal bath there.

These considerations led us to try the additional numerical experiments of subjecting a giant gaseous protoplanet to a thermal bath which rises and falls in temperature on the time scale of about 10^5 years which is characteristic of the primitive solar nebula, having an amplitude which varies with the presumed region of the primitive solar nebula which the experiment is intended to simulate.

The results for the Jupiter region experiment were very interesting. A conservative view was taken of the primitive solar nebula temperature to be expected in that region, with the nebula achieving a maximum temperature of just over 40 K at a little more than 5×10^4 years. A 1 $M_{♃}$ protoplanet was subjected to a thermal bath with these conditions. As the bath temperature rose, the flow of energy to the surface diminished but always stayed positive; the protoplanet thus survived through the peak of the thermal pulse at the surface and completed its evolution on a somewhat retarded time scale.

However, when the amplitude of the thermal pulse was increased to be more characteristic of that to be expected in the asteroid belt, the flow of energy to the surface of the protoplanet ceased, and energy flowed into the surface, causing the envelope of the protoplanet to undergo a very large expansion long before the peak of the thermal pulse. This run came to an end because the increasing rapidity of expansion of the surface caused the intermodel time step to become extremely small. It was evident that this situation would hold every–where in the inner solar nebula.

An argument has previously been given that in the inner solar nebula the growth of the sun could compete with the evolution of the giant gaseous protoplanets and would succeed in tidally stripping the envelope off the core of the protoplanet (4). It was envisaged that such a core would have formed by rainout of small mineral droplets suspended in the gaseous envelope of the protoplanet (5). The present results cast some doubt on the likelihood of this scenario but suggest an alternative scenario.

What appears now to be likely is that the evolution of giant gaseous protoplanets can survive the thermal pulse of solar nebula evolution provided they are in the outer solar nebula. However, in the inner solar nebula the evolution of the protoplanets will be halted by the thermal pulse of the solar nebula evolution, to be followed by rapid thermal evaporation of the envelope. If the present result is typical, the central temperature of these inner protoplanets may not even achieve 100 K.

Whether these inner protoplanets will have a lasting effect on the development of the solar system thus depends upon the unknown ability of cold interstellar grains, initially present in the protoplanet envelope, to clump together into sufficiently large sizes (6) to fall through the gas toward the center of the protoplanet faster than the gas evaporates away from the envelope. If this can happen on a sufficient scale, then the energy released by the falling grain clumps will cause a radically different evolutionary behavior in the cores of the inner protoplanets and may lead to substantial planetary bodies. A variety of additional investigations will be needed to pursue these possibilities.

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