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EFFECTS OF A GIANT IMPACT ON URANUS. W. L. Slattery, Los Alamos National Laboratory, and W. Benz and A. G. W. Cameron, Harvard-Smithsonian Center for Astrophysics. (Press version)

Tilt of Uranus Axis. What is often regarded as one of the most distinguishing and unique properties of the Uranus system is the fact that its rotational axis is tilted 97 degrees to the plane of the ecliptic (the plane in which the planets rotate around the Sun). The planet rotates with a period of 17.24 hours, and this rotation is thus actually in a retrograde direction.

However, from the point of view of the origin of the Uranus system, what counts is not that the rotation is actually retrograde, but rather that the tilt of the axis is not close to zero. If a planet is assembled from a very large number of small objects, then its rotation is expected to be prograde and the angle of inclination small. For example, Jupiter and Saturn are mostly composed of hydrogen and helium, which are expected to have been collected into the planet as gases, and indeed their tilts are small and their rotations are prograde. In the case of Uranus, only about 15 per cent of the mass is hydrogen and helium, and the remaining material, primarily water, ammonia, hydrocarbons, rock, and iron, can all be collected into the planet in solid form. This means that much of this material can have been assembled into bodies of intermediate size before colliding with Uranus. With only a very small number of these bodies in the mass range around 10 per cent of the Uranus mass, the angular momentum brought in when the largest of these collides with Uranus can become a large part of the final angular momentum now possessed by the planet. When this largest planetesimal collides, the direction of the collision is essentially random. Thus the final direction of the spin axis of the planet will also be essentially random.

When we wish to do a numerical simulation of this largest planetesimal collision, the actual angle of the collision plane is not meaningful; what is meaningful is the value of the angular momentum transferred to the growing planet. We choose to measure this in terms of the rotation period that the planet acquires following the collision, having started at the beginning of the collision with no rotation at all. We shall take as a measure of a successful simulation of a Giant Impact on the planet that the rotation period should become 17.24 hours or less. It is obvious that this criterion can only be regarded as an approximate one, since the final rotation rate will depend to some degree upon the collisions with the next largest group of planetesimals.

The Satellites of Uranus. Uranus has a compact system of regular satellites lying in the plane of its equator; these revolve around the planet in the same direction as its rotation, so that they are retrograde satellites.

Such a system of regular satellites will tend to line up their orbital planes to match the equatorial plane of the planet. If the planet were slowly, over something like a million year time period, to tilt its rotation axis relative to the plane of the ecliptic, then the plane of the satellite orbits would follow. However, if the rotation axis were suddenly tilted, as in a major collision, there would be no time for the orbital planes of the satellites to tilt with it. If the tilt were more than 90 degrees, then the orbital planes of the satellites would still be attracted to the equatorial plane, but in this case the satellites would revolve in a direction opposite to the rotation of the planet. For the orientation that Uranus now has, these would become prograde satellites. If the large tilt of the Uranus axis were produced by a Giant Impact, a pre-existing set of regular satellites could not tilt their orbital planes to match the new axis.

This gives rise to the hypothesis that the existing set of regular satellites might have been produced as a consequence of the Giant Impact itself. These satellites have mean densities 1.4 times that of water, about what you would get with a solar mix of ices (i. e., water, ammonia, and hydrocarbons), rock, and iron. In any event, it is clear that it is not sufficient for the Giant Impact just to deposit the ices in orbit; rock and iron must also be placed in orbit either from the Giant Impact itself or due to trapping of infalling solid materials in the equatorial plane by the ices left there by the Giant Impact. This question makes it particularly interesting to determine those Giant Impact parameters that leave rock and iron in orbit in addition to ices.

The Calculations. The simulations of possible Giant Impacts were carried out using Cray supercomputers at Los Alamos. The technique used is called smooth particle hydrodynamics (SPH). In this technique the material in the proto-Uranus planet and in the Impactor is divided into a large number of particles which can overlap one another so that local averages over these particles determine density and pressure in the problem, and the particles themselves have their own temperatures and internal energies. During the course of the simulation these particles move around under the influence of the forces acting upon them: gravity and pressure gradients. This is the technique that we have used to study collisions involving large bodies in the terrestrial planet region, particularly in connection with the problems of the origin of the Moon and of the high mean density of Mercury.

There are a number of uncertainties involved in the construction of models of the proto-Uranus and the Impactor that reflect our uncertainties about the manner in which these bodies were formed. We do not know when the Giant Impact might have occurred, but we think it would have been early in the life of the solar system, late in the general planetary accumulation process. For this reason we can use present-day models of Uranus only as a general guide, since the precollision Uranus was probably hotter than now, and it may have been more thoroughly mixed, with rock and iron dissolved in a convective atmosphere. However, we have followed conventional planetary structures by giving both the proto-Uranus and the Impactor an iron core surrounded by a rock (dunite) mantle. The Impactor was given an atmosphere composed of the ices H_2O, NH_3, and CH_4 in relative solar proportions. The atmosphere of the proto-Uranus was composed of these ices with an additional 2 $M_\oplus$ of hydrogen and helium mixed into them.

Simulations of possible Giant Impacts were made with the SPH code. We used 5000 particles in the proto-Uranus and 3000 particles in the Impactor. The physical properties of the materials used in the models are provided by their equations of state, which we obtained from a variety of sources.

Many numerical simulation runs were made, varying the mass of the Impactor between 1 and 3 $M_\oplus$ (but keeping the sum of the Impactor and proto-Uranus masses equal to that of Uranus today), and varying the angular momentum in the collision. The velocity of the Impactor at infinity in all the simulations was set at 5 km/sec.

A summary of all the simulations is shown in the figure. A horizontal line is drawn at the present value of the Uranus rotational period, 17.24 hours. The angular momenta on the abscissa are in units of 10^{43} gm cm^2/sec. The large range in collisional angular momenta corresponds to a small range of planetary rotational periods because part of the Impactor can sometimes escape from the system following the collision. A low angular momentum collision leads to core impact and absorption of the Impactor. Higher values of the angular momentum will lead to an atmospheric passage which slows down the Impactor, which then rises to a height of several planetary radii, with its core tidally sheared and separated from the atmosphere, to be followed by an infall that absorbs most of the Impactor core in the core of proto-Uranus.

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Most of the collisions leave ice in orbit. The energy released by the impact heats the proto-Uranus so much that the ice in orbit will be in gaseous form in the temperature field of the atmospheric radiating surface. Some of the collisions also leave some rock in orbit. These collisions are shown by filled symbols in the figure.

None of the simulations with an Impactor mass of 1 $M_\oplus$ leaves Uranus rotating with a period as short as the present-day value, although some of them come close; this Impactor mass can therefore be stated as a lower limit to the probable Impactor mass needed. An Impactor mass of 3 $M_\oplus$ succeeds over a wide range of collisional angular momenta in producing a Uranus rotation period shorter than at present, which we regard as acceptable, but in none of the cases is rock left in orbit. This is not necessarily fatal for the satellites, because an orbiting disk may capture significant amounts of rock-containing planetesimals that impact upon it; we are almost completely ignorant of the satellite accumulation conditions. However, for all Impactor masses in the range 1.3–2 $M_\oplus$ there were collisions which both spun the planet fast enough and left rock and ice in orbit.

Thus the simulations have not selected a narrow range of Giant Impact conditions that would be needed to produce the observed Uranus system, but have proved to be quite permissive. We believe that the high temperature and mixing results of the collisions will be of interest to those trying to model the history of the system.