The Formation of Martian River Valleys by Impacts

O. B. Toon, Department of Atmospheric and Oceanic Sciences and Laboratory for Atmospheric and Space Physics, Camous Box 392, University of Colorado, Boulder, Co 80309-0392 toon@lasp.colorado.edu

Introduction: Mariner 9's 1971 discovery of desiccated river valleys on Mars produced a long search for possible mechanisms that could cause water to flow over the Martian surface, which is now dry, cold and inhospitable. The discovery of apparently youthful gullies on the banks of Martian craters and valleys suggests that mechanisms are still active on the planet that can lead to water flow. There are also a variety of channels that appear to have local (or even distant) ground water sources associated with volcanic or geothermal activity, or perhaps nearby impacts events. These have ages scattered over Martian geologic history. However, the river valley networks of greatest interest are found only on the oldest Martian terrains and are believed to be about 4 billion years old. Unlike gullies and channels with local sources, the river valley networks suggest that it once rained on Mars.

Most of the mechanisms currently being considered to explain the rivers depend on a different atmospheric mass or composition than found presently on Mars. They also invoke the concept of a warm, wet early Mars, with lakes and seas for a prolonged period, perhaps hundreds of millions of years. Maybe Mars was an ideal place for life to arise, as it did on Earth under these climate conditions.

These ideas about changing the atmospheric composition of Mars parallel those for the early Earth, where it is thought that greater amounts of carbon dioxide, methane and other reduced gases kept our planet warm in its early history despite the lower solar luminosity. Keeping these planets above freezing when the solar luminosity is low is called the faint young sun problem. Unfortunately, thirty years of trying the path of a different atmospheric composition than at present has not produced a definitive explanation for Martian rivers. Carbon dioxide is not a powerful greenhouse gas and cannot raise the Martian global average temperature above freezing with lowered solar luminosity. So much carbon dioxide is needed for any appreciable greenhouse effect that it begins to condense in models either at the poles or in the atmosphere. More is needed. Methane, ethane, and sulfur dioxide have all been proposed for Mars, but none of these have been shown yet to be both adequate and chemically stable. Moreover, both methane and sulfur dioxide are likely to produce photochemical hazes, which will cool the planet and thereby counteract the greenhouse potency of the parent gases. It is well known that volcanic injections of SO_2 into Earth's atmosphere leads to significant net cooling by the production of highly reflective sulfuric acid aerosols. In addition, sulfate deposition on Mars occurred after the formation of the river valleys.

Impacts and Martian Rivers: In contrast to the greenhouse ideas, Segura et al. (1) suggested that the ancient river valley networks resulted from large impacts occurring in the early history of Mars. There are three phases to the impact development of rivers, which we will discuss. First, large impacts generate steam atmospheres because of the vast amounts of energy released in the impact, and the likelihood that the impactor and target will contain large amounts of water. The steam atmosphere will slowly cool. As it cools, very hot rain will fall, likely at rates similar to those on current Earth. Such rainfall accumulated over many impacts can partly explain the erosion inferred for this period in Martian history (2). Secondly, the water vapor added to the atmosphere can act as a powerful greenhouse gas and possibly even produce a prolonged period of relatively warm temperature with rainfall and a hydrological cycle (2,3). On Earth water is the major greenhouse gas, and in greenhouse models for the early Martian climate it is really water that is the principal radiator. Finally, by mobilizing water over much of the planet the impacts promote water and ice migration back to the coldest part of the planet, usually the poles, after the event. This migration can also cause seasonal melting and water flow, perhaps in the manner currently producing the Martian gullies (4).

The Evidence: The mass deposited (and volatiles released) by impacts is large, and comparable to the mass from the Tharsis volcanic construct. Steam atmospheres formed after large impacts whose craters remain on the surface can produce more than 600 m of rainfall, followed by rainfall from water vapor greenhouse atmospheres and snowmelt. The erosion rates from water produced by impacts that created the craters currently visible are somewhat less than suggested for the Noachian. There are several possible explanations for this difference, and it is possible erosion rates are overestimated because the burial of small craters by global debris layers from impacts has not been considered. Rainfall after the Noachian was low because the impact rate, and CO_2 pressure has been low.

Recent dating shows that the last flow in the river valley networks occurred at a similar time in all the networks. This time was also a period when many large impacts occurred. For example the last water flows postdate the formation of the Hellas basin by only a few hundred million years, and are contemporaneous with the formation of the Argyre basin. The bulk of Tharsis volcanic construct may have also formed in this two hundred million year period.

Impacts have the motive, the means, and the opportunity to have caused the river valleys. Their motive is to release incredible amounts of energy when the impact occurs. The means of making the rivers is to produce steam atmospheres, which release very hot rain to the surface. They have no alibi, the rivers are contemporaneous with large impacts.

The idea that impacts produced the Martian rivers suggests that early Mars was largely cold and dry, with short periods of terrestrial rainfall rates probably leading to short-lived lakes and rivers. This climate would likely not be as hospitable to life as early Earth's, though there would certainly be places where life might still have gained a foothold, particularly in the regolith.

Relatively little attention has been given to developing, testing or proving the idea that impacts caused the Martian rivers. The jury may be out, but impacts are clearly guilty.

References:

[1] Segura T, Toon OB, Colaprete A, Zahnle K. (2002) *Science* 198,1977-80. [2] Segura T., Toon OB, Colaprete A. 2008 *J. Geophys. Res.* 113:E11007, doi:10.1029/2008JE003147. [3] Colaprete A, Haberle RM, Segura TL, Toon OB, Zahnle K. 2004 Paper 8016. Workshop on the Role of Volatiles and Atmospheres on Martian Impact Craters, Lunar and Planetary Institute, Laurel, Md.:11– 14. [4] Williams KE. Toon OB, Heldmann JL, Mellon MT. 2008 *Icarus* 200:418-25.