THE LATE HEAVY BOMBARDMENT: POSSIBLE INFLUENCE ON MARS. D. M. Burt[1], L. P. Knauth[2], and K. H. Wohletz[3] [1]School of Earth and Space Exploration, Arizona State University, Box 871404, Tempe, AZ 85287-1404, dmburt@asu.edu, [2]same, knauth@asu.edu, [3]Los Alamos National Laboratory, Los Alamos, NM 87545, wohletz@lanl.gov.

Introduction: From orbit, Mars appears to be as heavily cratered as Earth's moon. The cratering record is best exposed on the ancient Southern Highlands; in the Northern Plains it is largely covered by a thin veneer of younger sediment and lavas. The martian cratering is widely assumed to date from the same episode of bombardment that cratered the Moon (the so-called Lunar Cataclysm). On the basis of radiometric dating of returned lunar impact melts, this episode has tentatively been assigned to the interval 4.0-3.8 Ga. The Late Heavy Bombardment (LHB) on Mars and other terrestrial planets, if it occurred, probably spanned the same geologically short time interval.

Somewhat surprisingly, given the wide discussion of the LHB for the Moon and Mercury, current and past geological literature on Mars tends to ignore this apparent spike in cratering, and rather implicitly assumes that the bombardment of Mars was continuous from its formation at about 4.5 Ga until about 3.8 Ga, an interval called the Noachian. In light of the LHB, the Noachian interval of Mars may actually have been rather short, with the record of the first half-billion years having been largely destroyed or buried (as on Earth).

The excellent preservation of the martian cratering record from 3.8 Ga on probably implies that Mars has been dry and cold since then. Other than continued cratering at a much reduced rate, the major geological process appears to have been extremely slow erosion and deposition by the wind. Important local contributions were made by basaltic volcanism, landslides and debris flows, ground ice (leading to terrain softening), glaciers (including rock glaciers), catastrophic flooding in outflow channels, and extremely minor chemical and physical weathering. Still, the ancient craters are all there. The major reason for their preservation is probably the LHB itself.

Compared to Earth, Mars is small and much farther from the Sun. Whatever its nature beforehand, the catastrophic cratering of the LHB, in addition to completely resurfacing the planet, should have resulted in catastrophic loss of hydrosphere and atmosphere to space. How then to explain the widespread evidence of ancient drainage networks, crater lakes, buried clay horizons, and surface sulfates (including acid sulfates)? These features are widely cited as evidence that Noachian Mars was warm as well as wet, and furthermore was literally bathed in sulfuric acid, supposedly (acid fog model) owing to atmospheric enrichment in volcanogenic sulfur dioxide (SO_2) to provide the greenhouse warming that carbon dioxide (CO_2) couldn't.

Inasmuch as these "warm, wet, acid" geological features coincide in time and space with the craters of the LHB, a simpler hypothesis might be that they are directly related. That is, the LHB itself can probably account for most of them, and especially their transient nature, although local volcanism, especially in the Tharsis region, was occurring at the same time.

Geological Changes. Before the onset of the LHB (i.e., prior to 4.0 Ga), Mars probably had more of an atmosphere and hydrosphere than at present; it also appears to have had a magnetic field (but none since). Given its distance from the Sun, and apparent inability to retain a thick atmosphere, most surface water was probably present as ice, nevertheless. Freezing of surface water would concentrate soluble salts in dense brines beneath the ice; salts would crystallize if temperatures were cold enough or enough ice sublimed. In other words, brine freezing (probably with ice sublimation) provides a possible alternative to direct brine evaporation for crystallizing salts [1].

Following each major impact, or at the height of the LHB (when many smaller impacts followed in close succession), enough steam should have been generated to create a temporary greenhouse, and condensation of and alteration by this steam could explain contemporaneous water-related features - clays, drainage networks, and lakes. If the impact target was rich in iron sulfides or various sulfate salts, the steam condensate could have been acid (i.e., acid rain). However, such acidity would have been ephemeral, given that Mars consists of basic silicates (silica or SiO_2 combined with MgO, FeO, CaO, and some Al_2O_3). That is, the liquid acid would have reacted with (neutralized itself against) basaltic rock, unless flash freezing or evaporation preserved it in the form of crystalline ferric acid sulfates, such as those found by the two rovers. Another way to create this mine dump mineralogy [2] would be for the impact to scatter shattered iron sulfides, which could later oxidize during damp diagenesis (the Roger Burns method). Neutral salts could similarly result from impact scattering of salty target materials or flash evaporation of brines. The important point is that acid surface waters are not required to make sulfate salts ("evaporites"), because salty impact deposits could have derived their salts via impact reworking of salts of various origins from various target areas [1]. The acid sulfates could be direct impact condensates or sulfide oxidation products.

By the tail end of the LHB (that is, by the time of the near-surface geological interval investigated by the two rovers Spirit in Gusev Crater, and Opportunity at Meridiani Planum), most of the martian hydrosphere and atmosphere had presumably already been lost to space (via impact erosion), and Mars would have been cold and dry. In part, impacts rework older impact deposits. Impact-generated steam would probably condense as snow or ice, at least far from the impact site. Lack of exposure to liquid water presumably accounts for the excellent preservation of features (including metastable acid sulfates), lack of salt recrystallization, and minimal erosion at these two surface sites.

Impact Surge Deposits and Spherules. Although it is smaller and colder and its surface is far older, Mars does have two important features in common with Earth - the presence of an atmosphere and of abundant subsurface volatiles (mainly water on Earth, mainly ice on Mars). These features mean that the LHB on Mars should have been distinct from the LHB on dry, atmosphereless bodies such as the Moon and Mercury. The young martian rampart craters, believed to form via impacts into an icy substrate, reflect this distinctness. On Earth, cross-bedded fine-grained sediments, locally containing various types of small spherules (glassy condensates and accretionary lapilli), are known to be deposited via explosions that vary from nuclear to volcanic to impact-derived. These explosion-deposited sediments (so-called surge or base surge deposits) can greatly resemble sediments deposited by flowing water or wind, a fact that has led to multiple misattributions [3]. In places, small radial scours caused by vortices, or bomb sags caused by the landing of ballistic ejecta, can help identify such sediments. In this regard, a bomb sag has tentatively been identified in the cross-bedded surge beds at Home Plate, Gusev Crater and a deep scour is present at the top of a large cross bed in the Burns Cliff exposure, Endurance Crater, Meridiani Planum.

Surge deposits can vary from wet to dry, depending on the initial steam content. Spherical accretionary lapilli typically form in rather wet deposits, via condensation of sticky steam on particles in a turbulent, dilute density cloud. Accretionary lapilli, unlike sedimentary concretions, tend to be strictly size and shape limited and unclumped; they also can contain high temperature minerals. Millimetric spherules of unspecified composition occur in a distinctive horizon beneath Home Plate in Gusev Crater; somewhat larger (up to about 5mm) and more abundant spherules occur in cross-beds in various near-surface horizons along the Opportunity Rover traverse in Meridiani Planum. The most common (at least 50%) phase in these lapilli is the crystalline, specular, high temperature form of hematite (so-called gray hematite, with detected enrichment in Ni); their blue-gray color led to the spherules initially being called “blueberries”. Other than some doublets and a linear triplet, the spherules tend to be unclumped and uniform in size (within a given horizon); they show no evidence of concentration by flowing or mixing groundwaters. Wind erosion has left them exposed as a lag deposit uniformly exposed over an area hundreds of km across.

Steam Alteration. A common phase in basaltic surge deposits (phreatomagmatic types, wherein steam explosions result from explosive mixing of magma and water) is yellow-orange palagonite, or hydrated and oxidized volcanic glass. Palagonite is believed to be extremely common all across Mars, and may partly be responsible for its distinctive color. Rather than forming by volcanism, palagonite could have originated by hydration and oxidation of basaltic impact melts in steamy impact surge clouds.

Terrestrial impact cratering, in the presence of water or ice, commonly results in silica alteration and deposition by hot springs. Given the low atmospheric pressure on Mars, acid fumarolic or steam alteration should be more common than hot springs. Such alteration, followed by impact scattering, could account for the silica-rich fragmental horizon recently identified beneath Home Plate, Gusev Crater. This horizon occurs above the one containing the spherules.

Conclusion: Impact surges seem to require either a volatile-rich target or an existing atmosphere or both, as on Mars. By the tail end of the LHB, when the impact surge deposits (our interpretation [4]) and spherules at Meridiani Planum and Home Plate (Gusev Crater) formed, Mars was already dry and cold. Surface waters are not indicated at that time (i.e., by available evidence either at Meridiani or Gusev), although they probably were ephemerally present earlier in martian history (especially during the most intense period of bombardment). Mars is indeed an impact-dominated planet, and many of its most interesting features apparently date from and probably were caused by the LHB.

References: [1] Knauth, L.P. and Burt, D.M. (2002) *Icarus 158*, 267. [2] Burt D.M et al. (2006) *Eos, 87*, 549. [3] Burt D.M. et al. (2008) *JVGR* (in press). [4] Knauth L.P. et al. (2005) *Nature, 438*, 1123.