Development of a Concept:

The Inner Solar System Impact Cataclysm Hypothesis &

The Impact-Origin of Life Hypothesis

The Chicxulub impact event and its link to the Cretaceous-Tertiary (K/T) boundary mass extinction event (e.g., Kring et al., 1991; Hildebrand et al., 1991; Kring and Boynton, 1992) demonstrates that impact cratering can affect both the geologic *and* biologic evolution of a planet as proposed by Nobel-winning L. Alvarez and others. This has led scientists to wonder if impact cratering may have affected the evolution of life at other times. For example, several teams, including one led by Dr. Kring, have been examining the causes of two of the other "big five" mass extinction events on Earth at the Permian-Triassic (P/T) and Triassic-Jurassic (T/J) boundaries.

Pushing farther back in time, Dr. Kring has also been examining the earliest impact events to affect Earth to determine if impact cratering may have affected the origin and early evolution of life. Previous Apollo-era analyses suggested the Moon was severely bombarded ~3.9 billion years ago, leading to the concept of a lunar cataclysm. As summarized below, Dr. Kring and his colleagues have been testing this hypothesis and finding that new evidence supports the idea that the Moon was severely bombarded nearly 4 billion years ago. He has also argued that this impact cataclysm affected Earth and all other inner solar system planetary surfaces, a concept now known as the inner solar system impact cataclysm hypothesis. He further suggests that the impact events delivered biogenic elements and, more importantly, created subsurface hydrothermal systems that were crucibles for pre-biotic chemistry and provided habitats for the early evolution of life, a new concept that he has called the impact-origin of life hypothesis.

Exploring how impact cratering may affect the origin, evolution, and distribution of life: The Impact-Origin of Life Hypothesis

D.A. Kring, "Impact events and their effect on the origin, evolution, and distribution of life," *GSA Today 10*, no. 8, pp. 1-7, 2000. **Invited paper.**

D.A. Kring, "Environmental consequences of impact cratering events as a function of ambient conditions on Earth," *Astrobiology 3(1)*, pp. 133-152, 2003. **Invited paper.**

Conclusion: Although impact events can be devastating (e.g., our discovery of the Chicxulub impact crater and its link to the K/T boundary mass extinction), impact events early in Earth history may have produced vast subsurface hydrothermal systems that were critical to the early development of life. Over 20,000 craters with diameters from 20 to >1000 km were produced on Earth.

Testing the lunar cataclysm hypothesis

B.A. Cohen, T.D. Swindle, and **D.A. Kring**, "Lunar meteorites support the lunar cataclysm hypothesis," *Science 290*, pp. 1754-1756, 2000.

I.J. Daubar, **D.A. Kring**, T.D. Swindle, and A.J.T. Jull, "Northwest Africa 482: A crystalline impact melt breccia from the lunar highlands," *Meteoritics and Planetary Science 37*, pp. 1797-1813, 2002.

B.A. Cohen, T.D. Swindle, and **D.A. Kring**, "Geochemistry and ^{40}Ar-^{39}Ar geochronology of impact-melt clasts in lunar highlands meteorites: Implications for lunar bombardment history," *Meteoritics and Planetary Science 40*, pp. 755-777, 2005.

Conclusion: New analyses of impact melts in lunar meteorites are consistent with the lunar cataclysm hypothesis, suggesting the Moon and Earth were severely bombarded in a brief interval of time approximately 3.9 billion years ago. This event is responsible for most of the impact craters on the ancient surfaces of the Moon and would have similarly affected Earth.

The cataclysm affected the entire inner solar system, including Mars; Geochemical fingerprints indicate asteroids were the source of the bombarding debris

D.A. Kring and B.A. Cohen, "Cataclysmic bombardment throughout the inner solar system 3.9-4.0 Ga," *Journal of Geophysical Research 107(E2)*, pp. 4-1 through 4-6, doi: 10.1029/2001JE001529, 2002.

Conclusion: Analyses of rock samples from a variety of asteroids and Mars indicate the bombardment affected the entire inner solar system ~3.9-4.0 billion years ago. Analyses of rock samples from lunar craters reveal the chemical fingerprints of asteroids, indicating they are the dominant source of impacting objects. Approximately 40 of the >20,000 craters produced on Earth had diameters of ~1000 km and several may have had diameters approaching 5000 km in diameter. At the same time, over 6400 craters with diameters >20 km may have been produced on Mars.

Geological fingerprints confirm that asteroids were the source of the inner solar system cataclysm

R.G. Strom, R. Malhotra, T. Ito, F. Yoshida, and **D.A. Kring**, "The origin of planetary impactors in the inner solar system," *Science 309*, pp. 1847-1850, 2005.

Conclusion: The size distribution of impact craters on the ancient surfaces of the Moon, Mars, and Mercury confirm that the source of impacting debris was the main asteroid belt. Thus, we now have two completely independent sets of data pointing to asteroids: (i) Cosmochemical evidence in the form of chemical fingerprints of asteroids in lunar impact melts (Kring and Cohen, 2002) and (ii) Geologic evidence in the form of crater sizes (Strom et al., 2005). The asteroid belt was sampled in a size-independent manner, implying that resonances swept through the asteroid belt. This implies, in turn, that Jupiter's orbit changed. Thus, evidence from the Moon may help reveal the accretional and orbital evolution of the large gaseous planets in the outer solar system.

Delivery of water and related biogenic elements

D. A. Kring and B. A. Cohen, "Cataclysmic bombardment throughout the inner solar system 3.9-4.0 Ga," *Journal of Geophysical Research 107(E2)*, pp. 4-1 to 4–6, 10.1029/2001JE001529, 2002.

J. J. Barnes, **D. A. Kring**, R. Tartèse, I. A. Franchi, M. Anand, and S. S. Russell, "An asteroidal origin for water in the Moon," *Nature Communications 7*, 10 p., doi:10.1038/ncomms11684, 2016.

Conclusion: Although some water was added during the inner solar system impact cataclysm, most of it was delivered to the Earth during an earlier phase of accretion. The delivery of Earth's water and biogenic elements was dominated by asteroids, not comets. That same asteroid-dominated signature is also seen in the isotopic composition of water in the Moon's mantle. In other work, T. D. Swindle and D. A. Kring (2001) showed that comets would have delivered far more argon and other noble gases to Earth's atmosphere than is observed, further supporting an asteroidal origin for most of Earth's water and biogenic elements.

Impact-generated hydrothermal activity: Chicxulub provides a case-study

L. Zurcher and **D.A. Kring**, "Post-impact hydrothermal alteration in the Yaxcopoil-1 hole, Chicxulub impact structure, Mexico," *Meteoritics and Planetary Science 39*, pp. 1199-1221, 2004.

L. Zurcher, **D.A. Kring**, M. Barton, D. Dettman, and M. Rollog, "Stable isotope record of post-impact fluid activity in the Yaxcopoil-1 borehole, Chicxulub impact structure, Mexico," In *Large Meteorite Impacts and Planetary Evolution III*, (T. Kenkmann et al., eds.), *Geological Society of America Special Paper 384*, pp. 223-238, 2005.

O. Abramov and **D.A. Kring**, "Numerical modeling of impact-induced hydrothermal activity at the Chicxulub crater," *Meteoritics and Planetary Science 42*, pp. 93-112, 2007.

Conclusion: Hydrothermal systems occur across the entire diameter of a crater. Mineral alteration at Chicxulub indicates that peak temperatures in some regions of the crater may be temporarily too high for life, although vast regions should also be suitable for biologic activity as the systems cool.

Determining the thermal lifetime of impact-generated hydrothermal activity

O. Abramov and **D.A. Kring**, "Numerical modeling of an impact-induced hydrothermal system at the Sudbury crater," *Journal of Geophysical Research 109*, E10007, 16 p., doi: 10.1029/2003JE002213, 2004.

Conclusion: A convecting hydrothermal system in a ~200 km terrestrial crater can persist for several hundred thousand to over 1 million years. The subsurface environment suitable for thermophilic and hyperthermophilic life (50 to 100 °C) is up to ~50,000 km^3 in volume.

Application of concept to Early Mars

D.A. Kring and O. Abramov, "Impact-generated Hydrothermal Systems: Potential Sites for Pre-biotic Chemistry and Life on Early Earth and Mars," NASA Astrobiology Conference, Boulder, Colorado, 2005.

O. Abramov and **D.A. Kring**, "Impact-induced hydrothermal activity on early Mars," *Journal of Geophysical Research 110*, E12809, 19 p., doi: 10.1029/2005JE002453, 2005.

Conclusion: Impact-generated hydrothermal systems on early Mars can be long-lived (albeit not as long-lived as those on Earth), ranging from 50,000 to 700,000 years for craters 30 to ~200 km diameter. Larger impact basins may have had systems that existed for several million years.

Confirmation of concept for Mars

S.P. Schwenzer and **D.A. Kring**, "Impact-generated hydrothermal systems capable of forming phyllosilicates on Noachian Mars," *Geology 37*, pp. 1091-1094, 2009.

S.P. Schwenzer, O. Abramov, C.C. Allen, S.M. Clifford, C.S. Cockell, J. Filiberto, **D.A. Kring**, J. Lasue, P.J. McGovern, H.E. Newsom, A.H. Treiman, D.T. Vaniman, and R.C. Wiens, "Puncturing Mars: How impact craters interact with the Martian cryosphere," *Earth and Planetary Science Letters 335-336*, 9-17, 2012a.

S.P. Schwenzer, O. Abramov, C.C. Allen, J.C. Bridges, S.M. Clifford, J. Filiberto, **D.A. Kring**, J. Lasue, P.J. McGovern, H.E. Newsom, A.H. Treiman, D.T. Vaniman, and R.C. Wiens, "Gale Crater: Formation and post-impact hydrous environments," *Planetary and Space Science 70*, 84-95, 2012b.

S.P. Schwenzer and **D. A. Kring**, "Alteration minerals in impact-generated hydrothermal systems – Exploring host rock variability," *Icarus 226*, 487-496, 2013.

Conclusion: Abramov and Kring predicted we would discover that the Noachian crust of Mars was affected by impact-generated hydrothermal alteration whereas younger, post-cataclysm crust would have much less hydrothermal alteration. Observations by orbiting spacecraft confirmed that prediction. In the 2009 paper, the chemical and mineralogical evolutions of those systems were modeled. The results provide additional links between impact-generated hydrothermal activity during an early period of bombardment and a growing number of spacecraft observations. The 2013 paper expanded those models and the intervening papers explored the interaction of those systems with Mars cryosphere (2012a) and at the specific location of where the Mars rover Curiosity landed (2012b).

More geochemical fingerprints of an asteroid source of the bombardment

I.S. Puchtel, R.J. Walker, O.B. James, and **D.A. Kring**, "Osmium isotope and highly siderophile element systematics of lunar impact melt breccias: Implications for the late accretion history of the Moon and Earth," *Geochimica et Cosmochimica Acta 72*, pp. 3022-3042, 2008.

J. Liu, M. Sharp, R.D. Ash, **D.A. Kring**, and R.J. Walker, "Diverse impactors in Apollo 15 and 16 impact melt rocks: Evidence from osmium isotopes and highly siderophile elements," *Geochimica et Cosmochimica Acta 155*, pp. 122-153, 2015.

Conclusion: Analyses of samples from the Apollo 14, 15, 16, and 17 landing sites, plus a lunar meteorite, reveal more geochemical fingerprints of asteroids in melts produced during and near the end of the basin-forming epoch on the Moon.

Determining the collisional evolution of the asteroid belt and its capacity to provide impactors to the inner solar system

T.D. Swindle, C.E. Isachsen, J.R. Weirich, and **D.A. Kring**, "^{40}Ar-^{39}Ar ages of H-chondrite impact melt breccias," *Meteoritics and Planetary Science 44*, pp. 747-762, 2009.

A. Wittmann, T.D. Swindle, L.C. Cheek, E.A. Frank, and **D.A. Kring**, "Impact Cratering on the H-chondrite parent asteroid," *Journal of Geophysical Research 115*, 22 p., E07009, doi:10.1029/2009JE003433, 2010.

S. Marchi, W.F. Bottke, B.A. Cohen, K. Wünnemann, **D.A. Kring**, H.Y. McSween, M.C. De Sanctis, D.P. O'Brien, P. Schenk, C.A. Raymond, and C.T. Russell, "High-velocity collisions from the lunar cataclysm recorded in asteroidal meteorites," *Nature Geosciences 6*, pp. 303-307, 2013.

T.D. Swindle, **D.A. Kring**, and J.R. Wierich, "^{40}Ar-^{39}Ar ages of impacts involving ordinary chondrite meteorites," in *Advances in ^{40}Ar-^{39}Ar Dating: from Archeaology to Planetary Sciences*, Geological Society of London, Special Publications, *378*, 333-347, 2014. **Invited paper.**

Conclusion: Meteoritic samples from the interior of craters and their ejecta on the H-chondrite asteroid were studied to determine the chronology of impact events on that asteroid. The samples record collisions during the first 100 Ma of solar system history (reflecting the planetary accretion epoch), during an interval from ~3.5-4.0 Ga (consistent with an inner solar system cataclysm), and during sporadic events at younger times, particularly 300 to 500 Ma. The distribution of ages suggests energetic impacts were rare between accretion and the cataclysm and during a long stretch of time after the cataclysm. There are also hints that the oldest impact events were the largest crater-forming collisions.

Jump in the impact velocity when the cataclysm begins

S. Marchi, W. F. Bottke, **D.A. Kring**, and A. Morbidelli, "The onset of the lunar cataclysm as recorded in its ancient crater populations," *Earth and Planetary Science Letters 325-326*, pp. 27-38, 2012.

Conclusion: Using the tool developed by Strom et al. (2005 – described above), this study involved a more detailed examination of the crater size distribution in the three most ancient surfaces on the Moon. They revealed a subtle, but significant, shift in the size distribution of craters that is interpreted to indicate there was a doubling of the impact velocity of asteroids hitting the Earth and Moon. That jump in the impact velocity occurred between the formation of the South Pole-Aitken basin (the oldest and largest basin on the Moon) and the Nectaris basin (located near the Apollo 16 landing site).

First attempt to calibrate the impact flux from 4.5 to 3.5 billion years ago

A. Morbidelli, S. Marchi, W.F. Bottke, and **D.A. Kring**, "A sawtooth-like timeline for the first billion years of lunar bombardment," *Earth and Planetary Science Letters 335-356*, pp. 144-151, 2012.

Conclusion: By combining dynamical models, lunar crater size distributions, and abundances of impactor-derived siderophile abundances in lunar rocks, we calibrated the impact flux during the first billion years of lunar history. The work suggests a slightly broader, sawtooth-like flux profile, rather than a very narrow impact spike at 3.9 Ga. The work also predicts the age of the oldest and largest basin (the South Pole-Aitken basin) is >4.3 Ga.

Direct detection of projectile relics

K. H. Joy, M. E. Zolensky, K. Nagashima, G. R. Huss, D. K. Ross, D. S. McKay, and **D.A. Kring**, "Direct detection of projectile relics from the end of the lunar basin-forming epoch," *Science 336,* 1426-1429, 2012.

Conclusion: To determine the nature of the projectiles hitting the Moon, we have previously used chemical fingerprints in lunar impact melts (Kring and Cohen, 2002; Puchtel et al., 2008) and the size distribution of impact craters (Strom et al., 2005). A more direct measure, however, would be the direct detection of mineralogical and lithological remnants of the impactors that hit the Moon. With that concept in mind, new techniques were developed to inventory particles trapped within ancient regolith breccia samples collected by the Apollo astronauts. This paper reports the remarkable discovery of projectile relics from the end of the basin-forming epoch that indicates the projectiles were primitive asteroids. There is also a suggested shift to a more diverse population of asteroid impactors after the basin-forming epoch ended. If comets were involved in the basin-forming epoch, remnants of them elude us and were probably no more than 5 to 17% of the impactor population.

Revisiting the environmental conditions during the Hadean: The effect of impact bombardment on the early evolution of life

O. Abramov, **D.A. Kring**, and S.J. Mojzsis, "The impact environment of the Hadean Earth," *Chemie der Erde – Geochemistry 73,* 227-248, 2013. **Invited paper.**

S. Marchi, W.F. Bottke, L.T. Elkins-Tanton, M. Bierhaus, K Wünnemann, A> Morbidelli, and **D.A. Kring**, "Widespread mixing and burial of Earth's Hadean crust by asteroid impacts," *Nature 511*, 578-582, 2014.

Conclusion: Building on the work above (e.g., Kring 2000, 2003; Abramov and Kring 2004), we re-examined the effect thousands of impact events had on the surface of the Earth during the Hadean. In the first paper, detailed thermal modeling of the impact craters and the debris they deposited on the landscape shows that high-temperature environmental conditions occurred repeatedly, even though only a small fraction of the crust was melted at any one time. These conditions favor those types of organisms that can survive and/or thrive in hydrothermal conditions. In the second paper, we used the updated assessment of lunar impact flux (Morbidelli et al. 2012) and applied a sophisticated scaling of that flux to nearby Earth to determine the effect on the Hadean Earth. Up to 60-70% of the Earth's crust was reworked to a median depth of 20 km. These results are consistent with the distribution of crystallization ages among Hadean zircon crystals, which are the only remnants of the Hadean on Earth. The results also indicate three to seven impactors larger than 500 km hit during the Hadean and vaporized the world's oceans for short durations (<1%) during the Hadean.

Looking for evidence of early Earth on the Moon

In the early 1980's, Kring searched for early Earth fragments in soil samples collected by the Apollo astronauts. Nothing was found. More recently, his team developed new techniques for locating non-lunar particles in lunar regolith samples (e.g., Joy et al., *Science* 2012). That prompted a renewed search of the Apollo collection.

J. J. Bellucci, A. A. Nemchin, M. Grange, K. L. Robinson, G. Collins, M. Whitehouse, J. F. Snape, M. D. Norman, and **D. A. Kring**, "Terrestrial-like zircon in a clast from an Apollo 14 breccia," *Earth and Planetary Science Letters 510*, 173–185, 2019.

Conclusion: Seven chemical and mineralogical indicators suggest a rock fragment found in an Apollo 14 sample was produced in an oxidizing terrestrial environment, rather than a lunar environment. The data are consistent with the following scenario: The rock crystallized about 20 kilometers beneath Earth's surface 4.0-4.1 billion years ago. It was then excavated by one or more large impact events and launched into cis-lunar space at a time when impacting asteroids were producing craters thousands of kilometers in diameter on Earth. After the sample landed on the lunar surface, it was affected by several other impact events, one of which partially melted it 3.9 billion years ago, and which probably buried it beneath the surface. The sample is therefore a relic of an intense period of bombardment that shaped the Solar System during the first billion years. After that period, the Moon was affected by smaller and less frequent impact events. The final impact event to affect this sample occurred about 26 million years ago, when an impacting asteroid hit the Moon, producing the small 340 meter-diameter Cone Crater, and excavating the sample back onto the lunar surface where astronauts collected it in 1971. While no evidence of life was found in this sample, it suggests the principle of finding evidence of Earth's Hadean conditions on the Moon has merit. The granitic lithology also supports arguments for felsic crustal components on Earth as early as 4 Ga.