

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.

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 an ~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 km³ 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.

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 this 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.

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.

Conclusion: Analyses of samples from the Apollo 14 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*, in press, 2010.

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, during an interval from ~3.5-4.0 Ga (consistent with an inner solar system cataclysm), during sporadic events at younger times, particularly 300 to 500 Ma. The distribution of ages suggests 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.