National Aeronautics and Space Administration

YEARS 1-3 ***EXECUTIVE SUMMARY***

Center for Lunar Science and Exploration

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NASA LUNAR SCIENCE INSTITUTE

Chapter 7: Center for Lunar Science and Exploration (PI Dr. David A. Kring)

7.1: Executive Summary. The Lunar and Planetary Institute (LPI) and the Johnson Space Center (JSC) have a long and successful history of collaborative research and exploration activities that began with the Apollo program. The LPI and JSC have harnessed that heritage to develop the Center for Lunar Science and Exploration (http://www.lpi.usra.edu/nlsi/) to better support our nation's science and exploration activities. The Center is designed to (1) develop a core, multi-institutional lunar science program that addresses the highest science priorities identified by the National Research Council (NRC) for NASA; (2) provide scientific and technical expertise to NASA that will infuse its lunar research programs, including developing investigations that influence current and future space missions; (3) support the development of a lunar science community that both captures the surviving Apollo experience and trains the next generation of lunar science researchers; and (4) use that core lunar science to develop education and public outreach programs that will energize and capture the imagination of K-14 audiences and the general public. To meet those objectives, we developed programs for scientific research, exploration, training, and education and public outreach. Each of those programs and a summary of activities are presented here.

Science. The NLSI program fosters collaborative, multi-institutional work that takes advantage of long-distance networking technologies. We have, thus, organized a team involving faculty, students, and analytical facilities at Rice University, the University of Arizona, University of Houston, University of Maryland, and University of Notre Dame. We have also established international partnerships with faculty, students, and analytical facilities in Australia, India, Japan, and the United Kingdom. In 2½ years, we have published 30 peer-reviewed research papers, 164 extended conference abstracts, 74 conference abstracts, 2 policy white papers, 6 decadal survey papers, and 2 magazine articles.

At the core of the Center's activities is a series of studies (Fig. 7.1) to test the giant impact hypothesis for the Moon's origin; the lunar magma ocean hypothesis and its implications for differentiation of all terrestrial planets; and the lunar cataclysm hypothesis, which has become a critical measure of events involved in the accretion and orbital evolution of planetary bodies in both the inner and outer solar system. That period of bombardment may also be intimately linked with the origin and early evolution of life on Earth (Fig. 7.2). The scope of our work encompasses seven of the eight science concepts identified by the National Research Council (2007) for NASA's Science Mission Directorate (SMD), although our focus is on the highest-priority science concept (the bombardment history of the inner solar system is uniquely revealed on the Moon) and highest-priority goal (to test the lunar cataclysm hypothesis). It also addresses at least two priority questions of Planetary Sciences in the Decade 2013-2022 and provides baseline studies for the recommended New Frontiers South Pole-Aitken sample return mission. To illustrate our integrated approach, we outline a subset of our results regarding our investigation of the earliest collisions to have affected the Moon.

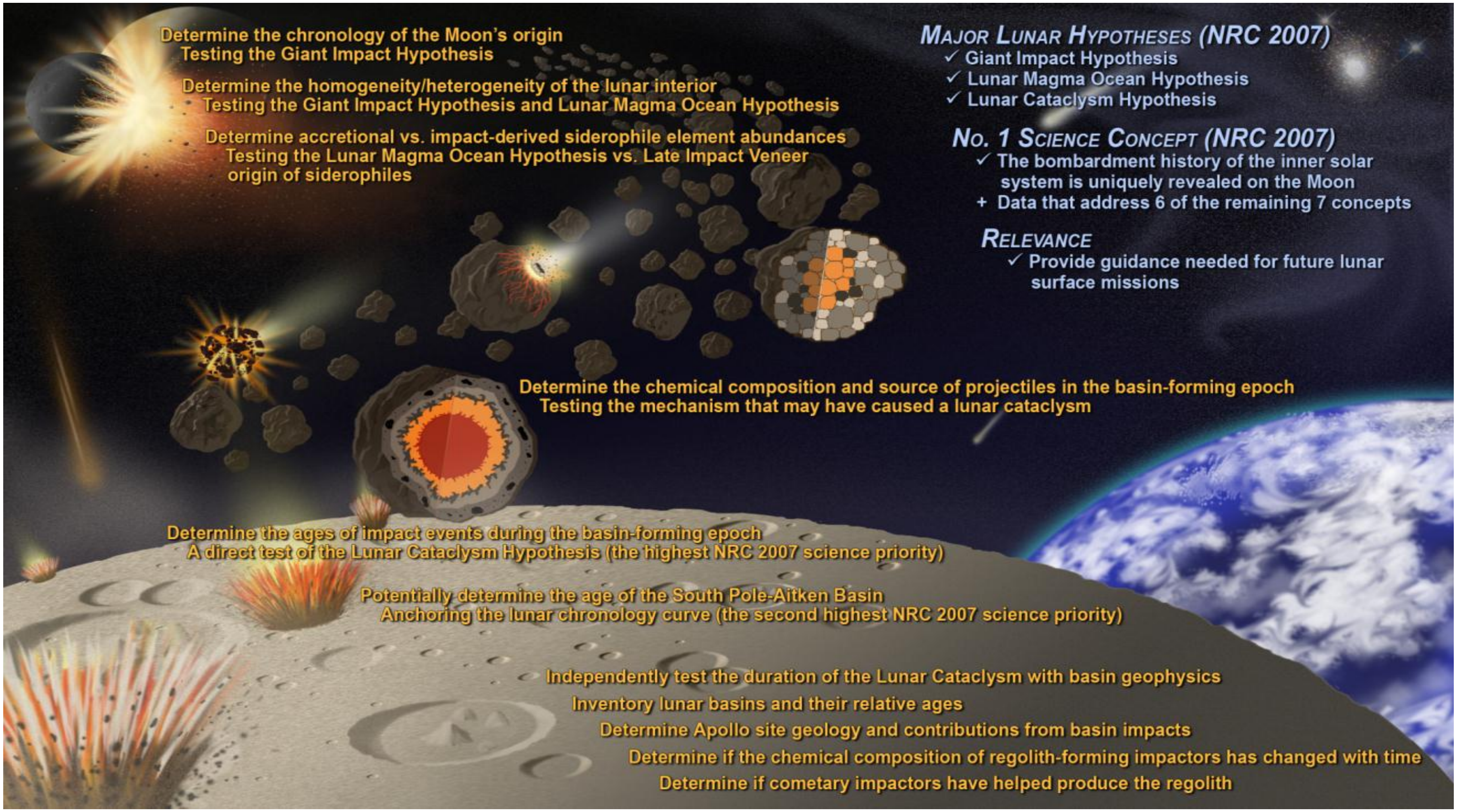

Fig. 7.1. The Center for Lunar Science and Exploration team is investigating impact cratering, which is the dominant geologic process affecting the lunar surface and intimately involved in the Moon's origin. The theme that runs through our science initiative is tied directly to the major lunar hypotheses, science concepts, and highest science priorities identified by the NRC (2007). Our projects trace the origin and evolution of the Moon from the hypothesized giant impact origin (upper left corner), through the collisional evolution of debris in the solar system (mid-panel) that produced the great basin-forming epoch on the Moon and potentially a lunar cataclysm (lower left), to the continued impact production and gardening of the lunar regolith (lower right). Scientific bonuses of this work include an evaluation of the Moon's primordial crust, diversity of crustal lithologies, and distribution of basin-epoch lithologies at future landing sites, which are additional targets of the NRC (2007) report.

We begin with the discovery of a spectacular meteoritic relic from a planetesimal collision that occurred before the Moon had even formed [Weirich et al. 2011]. After the Moon accreted, collisions repeatedly modified its crust and upper mantle. Hydrocode modeling of the formation of the oldest and largest basin on the Moon, the South Pole-Aitken Basin, indicates a significant amount of mantle material was melted and incorporated into a central melt zone [Potter et al., submitted], thus providing a key compositional parameter for the identification of impact melts associated with that event and its age. Modeling of other basins is underway [Potter et al. 2011], which is providing the input needed to evaluate post-impact evolution of the lunar crust [Kiefer et al. 2011]. We found that basins may have influenced stresses in the lithosphere and the eventual eruption of basalts on the lunar surface [McGovern and Litherland 2011]. In parallel, we used LRO data to show that the outer rings of the Orientale Basin, the youngest and best preserved basin, formed along 30 km deep normal faults [Nahm and Kring 2011] in a manner similar to that seen at the Chicxulub impact crater on Earth.

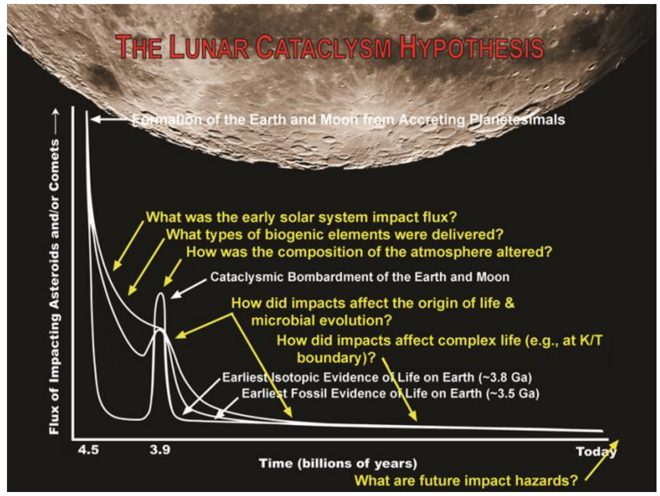

Fig. 7.2. A schematic diagram illustrating the lunar cataclysm hypothesis, uncertainties associated with it, and the fundamentally important questions associated with that impact flux. Apollo sample analyses suggest there was a spike in the impact rate about 3.9 Ga and that the last of the basin-forming impact events on the Moon occurred ~3.8 Ga. The magnitude and duration of that spike is unclear, as is the impact flux between 4.5 and 4.0 Ga. (After Kring, 2003).

During the basin-forming epoch, the Moon's crust and upper mantle were repeatedly affected by impacting asteroids. Using a new tool to probe the most ancient lunar terrains, we discovered a shift in the size distribution of craters that implies asteroid impact velocities doubled at the beginning of the lunar cataclysm, sometime between the formation of the South Pole-Aitken and Nectaris basins [Marchi et al. 2012], consistent with a shift in the orbits of Jupiter and other outer solar system planets. A new photogeologic assessment of the the Apollo 17 landing site suggests more basins were produced between the Serenitatis and Imbrium impact events than previously thought [Spudis et al. 2011], implying a far more dramatic lunar cataclysm.

We are continuing to probe the source of debris hitting the Moon during the basin-forming epoch and compare it to more recent times using newly developed techniques to measure highly siderophile elements and Os-isotopes. Analyses of Apollo impact melt samples [Galenas et al., 2011] indicate some were produced from known meteoritic sources, while others were produced by projectiles that are not represented in the current meteoritic inventory. Not only are we painting a definitive view of projectile sources, it is fueling a new assessment of the biogenic elements added to Earth.

Because impact melts are the key to determining the cadence of impact activity, we have developed easy-to-use analytical expressions for calculating impact melt volumes for impacts of any trajectory into the Moon and any other terrestrial planetary surface [Abramov et al., in press]. We are also mapping the location of impact melt deposits on the lunar surface that are suitable for future sample return missions [Öhman and Kring, 2012], while developing and implementing a training program for astronauts that may be tasked to collect those samples (Kring 2011; Kring and Hörz 2011; Kring and Lofgren 2011).

Exploration. We are using our team's extensive experience with lunar surface samples, impact cratered terrains, and volcanic terrains to integrate science and exploration activities. We led the scientific support for several lengthy simulations of missions to the Moon and near-Earth asteroids at the Black Point planetary analogue terrain in northern Arizona (Fig. 7.3). In 2010, for example, our team helped develop a detailed 28-day-long mission plan for the Malapert Massif region within the South Pole-Aitken Basin, which was then simulated at the Black Point site. This year we led the science plan for near-Earth asteroid mission operations. These simulations involve the Lunar Electric Rover/Space Exploration Vehicle and the astronaut office.

As the community develops the architecture and hardware to return to the lunar surface, our team has developed a series of studies to determine where on the lunar surface the NRC's highest science objectives can be achieved. We have determined that one of the best sites for testing the lunar cataclysm hypothesis is Schrödinger Basin [O'Sullivan et al. 2011; Kramer et al., in prep.]. At that locality, we should be able to determine the age of the oldest basin (South Pole-Aitken) and that of the second youngest (Schrödinger), thus bracketing nearly the entire basin-forming epoch. Interestingly, Schrödinger also contains volcanic deposits of Eratosthenian and Copernican age, thus providing two additional benchmarks in the evolutionary

Fig. 7.3. Team members have participated in four lunar and one near-Earth asteroid mission simulation at the Black Point Lava Flow planetary analogue site. Tests involved detailed crew traverses and a trade study between unpressurized crew rover and pressurized crew rover (seen here). Geologic tools were located on the aft deck of the rover. Crew egressed through suit ports on a platform near the geologic tool storage rack. Photo credits: NASA JSC (top) and David A. Kring (bottom).

stratigraphy of the Moon. We are currently developing mission concepts to Schrödinger using stand-alone robotic assets and robotic assets that are assisted by crew from an Orion platform at the Earth-Moon L2 position.

Training. Future space exploration depends critically on our ability to train young people. The Center is developing a pipeline of talent that feeds into research and development programs associated with both SMD and HEOMD. The Center's programs have engaged 11 post-doctoral fellows and ~100 graduate students thus far.

A highlight of graduate student training is our *Lunar Exploration Summer Intern Program*, which has hosted seven teams in an intensive and immersive study of lunar landing sites where the NRC (2007) science objectives can be addressed. Those results have been so successful that they have been repeatedly briefed to ESMD and HEOMD staff, including the Lunar Destinations portion of NASA's Human Spaceflight Architecture Team (HAT).

Another highlight of graduate student training is the *Field Training and Research Program at Meteor Crater* (Fig. 7.4), the world's best preserved impact crater. Skills developed during the training program have better prepared the students for their own thesis studies in impact cratered terrains on the Earth, Moon, Mars, and other solar system bodies. The research component has also led to significant discoveries at Meteor Crater (Kring et al. 2011, 2012).

Fig. 7.4. One of the highlights of our training activities is the Field Training and Research Program at Meteor Crater. In 2010 we hosted 19 Ph.D. and 5 M.S. students and in 2011 12 Ph.D. and 4 M.S. students. Here, four students are studying impact ejecta with CLSE PI Kring.

A third major component of our training activities is the *Lunar Consortium for Higher Education*, which involves a large number of university faculty who are developing on-line material that teachers anywhere in the world can access and incorporate into their classrooms.

Education and Public Outreach. The results of our science investigations are being mined to generate a dynamic education and public outreach (E/PO) program. Activities are designed to assist teachers with their classroom activities, and reach students at all levels. The Center for Lunar Science and Exploration is building on a long heritage of E/PO products generated by the LPI and JSC staff that feed forward to the university programs that we support (Fig. 7.5). We have, for example, sponsored lunar research projects at 19 high schools nationwide that involve 27 teams and 169 students, including those in under-represented and under-served populations. We have also created a series of library exhibits that have been distributed to 24 unique locations that have reached 100,000 people in special library programs thus far.

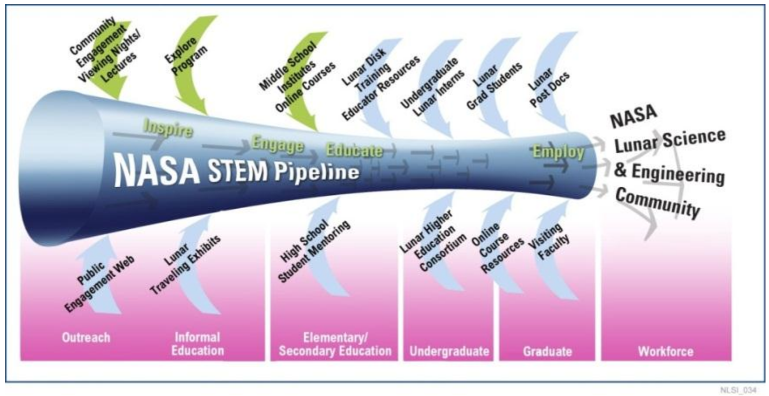

Fig .7.5. Outreach, informal education, and high school mentoring feed students into the undergraduate and graduate student training activities and, eventually, the professional science and exploration communities.

Cross-cutting Products. Our team has generated cross-cutting products that serve the science, exploration, education, and public communities. One of our product highlights is the *Lunar Science and Exploration Portal* (http://www.lpi.usra.edu/lunar/), which is designed to be an on-line gateway to lunar information. Over 5 million page views have been recorded thus far (>5000/day). That product includes a *Lunar Sample Atlas* (42,000 images), *Apollo Image Collection* (32,000 images), a *Virtual Microscope*, and an immense collection of lunar science and exploration documents.

Conclusions. We note that this integrated set of activities could not have been accomplished without the administrative and funding structure provided through the NASA Lunar Science Institute program. That architecture is very efficient and maximizes the productivity of the team and, thus, greatly enhances our ability to provide NASA the products it needs.

Our work continues to show that the Moon is the best and most accessible place in the Solar System to explore the fundamental principles of our origins.

Finally, the response from students has been amazing. Lunar missions are inspiring our youth and encouraging them to participate in science and technological fields, fulfilling another important objective for the nation.