DELIVERY OF PLANETARY EJECTA TO EARTH

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Orbital histories of ejecta from the terrestrial planets are numerically integrated to study their transfer to Earth. The regularized mixed-variable symplectic integration code includes the effects of the planets from Mercury through Neptune. Particles are followed until they impact a planet, strike the Sun, or cross the orbit of Jupiter. The distribution of transit times for Earth-impacting objects is compared with the cosmic-ray exposure data for the lunar and martian meteorites. This comparison is consistent with a recurrent ejection of small meteoroids due to impacts on their parent bodies. Long-range gravitational effects, especially secular resonances, strongly influence the orbits of many meteoroids and can increase meteoroid collision rates with other planets and even the Sun. These effects, and collisional destruction in the asteroid belt, result in shortened time scales and higher fluxes than previously believed, especially for martian meteorites. A small flux of mercurian meteorites appears possible; recovery of ejecta from the Earth and Venus is less likely.

A model is presented which calculates the expected transfer-age spectrum in terms of the impactor flux onto the Moon and Mars. The non-zero, but finite, age of the Antarctic ice sheet is crucial in understanding the different distributions of transfer ages in the lunar and martian cases. To match the data, most recently-arrived lunar meteorites must have been launched by impactors of diameter $D <$ 100 m which struck the Moon in the last few hundred thousand years. In contrast, martian meteorites were launched by impactors several kilometers in diameter that struck Mars several million years ago. The number of meteoroids launched by each impact must scale as D^2 in the lunar case, but $\approx D^3$ for Mars. Different surface properties for the Moon and Mars may account for these differences.

Biographical Sketch

Most thesis biographies seem to begin with birth, which has an inescapable logic that one must conform to. Brett James Gladman was born on April 19th, 1966 as his poor parents were attempting to drive from northern Alberta to Calgary (he being in a rush, as usual). Because his father was in the Royal Canadian Air Force, Brett spent much of his youth moving around Canada from military base to military base, which gave him a trait of social independence which has been both a strength and a weakness. Travel was a constant thing in his life, for even when not changing towns or occupations, his parents were constantly going off camping, with Brett, his brother Brad (14 months junior), and a trailer, in tow. During the long drives, Brett read voraciously although this produced many beratings from his father, who didn't want him to miss the "beautiful scenery" (which consisted of perfectly level central Canadian plains punctuated by the occasional heroic grain elevator). His father encouraged an interest in arithmetic during these trips by naming long strings of operations to be performed on an initial number ("Take 3, multiply by 10, subtract 2, divide by 4, ..."); an activity which Brett would be willing to do until it drove everyone nutty.

At the start of his teenage years Brett had no real idea of what he wanted to do with his life, but knew it would probably be in a field ending in -ology or -onomy (paleontology, geology, and astronomy were high on the list, reflexology never appeared, and gastronomy was a later addition). As is the case for many children, he was fascinated by space and dinosaurs. He had an addiction to computers in high school, but decided that he wanted the machine to be a tool instead of being the center of a career.

Near the end of high school, Brett happened to see a magazine article biographing a relativist, Dr. Werner Israel, at the University of Alberta. Since Brett had always thought that black holes were 'cool', he wrote Dr. Israel a letter expressing an interest in the subject and asking for some further recommended readings. The reply included an invitation to visit the university. This visit, and the kind advice of Dr. Israel, convinced Brett to enroll in a physics program, which he completed in 1988, receiving a B.Sc. (Honours) degree. While at the U. of A., he was most heavily influenced by the astronomer Dr. Douglas Hube, under whose guidance Brett performed a term-project to compute the orbit of the asteroid Vesta, which was photographed from the observatory on the roof of the physics building. Although the success of this project left something to be desired, it whetted Brett's appetite for mechanics and dynamics. For a change, Brett worked during his undergraduate summers at a nuclear medicine department at the Foothills hospital in Calgary, Alberta. While there Brett obtained an appreciation for the difficulties of applied science (the human body is poorly approximated by a sphere).

After a brief foray for a summer into general relativity (which Brett found somewhat dry) Brett fortuitously chose to attend Queen's University in Kingston, Ontario. There he worked with Dr. Martin Duncan, who was also fleeing general relativity and had begun working on solar system dynamics. Brett's M.Sc. thesis 'Symplectic integrations of test particle orbits in the outer solar system' applied new numerical algorithms to show that there were no stable orbits between the outer planets where small bodies could survive for the lifetime of the solar system. The degree was completed in August 1990.

Brett drew a huge breath in the summer of 1990 and elected to take a year away from university before continuing his studies. For several months Brett worked as a 'swamper' back home in Calgary, unloading several tonnes of margarine each day from cargo trucks. This experience firmly reinforced in Brett's mind the value of an education, although the manual labour was a refreshing change from sitting in front of computer terminals. However, the highlight and main purpose of the year's 'sabbatic' was a three-month vacation in Europe. Brett spent two months in northern Italy soaking up its art treasures and eating like a king. He then visited Salzburg, Bavaria (where he finally developed a taste for beer), and central France.

Brett arrived at Cornell in September 1991 and began working with Dr. Joseph A. Burns. A term project turned into a paper on theoretical dynamics (B. Gladman 1993. Dynamics of systems of two close planets. *Icarus* **106**, 247-263). Brett was also fortunate to be able to conduct a series of observations to search for, and recover, Kuiper-Belt comets at the Mount Palomar 5-meter telescope. Another term project evolved into an extended collaboration, which eventually produced a paper on satellite spin dynamics (B. Gladman, D. Quinn, P. Nicholson, and R. Rand 1996. Synchronous locking of tidally evolving satellites. *Icarus*, in press). Although these were interesting and rewarding studies, Brett still did not have a thesis topic, nor did he yet feel like a Cornellian. The purchase of a pair of Birkenstocks quickly solved the latter problem, and put Brett in line with a distinguished string of Burns' graduate students (in fact, the resemblance to his advisor began to reach frightening proportions in the late stages of this thesis).

Brett's doctoral thesis is the end product of a gradual evolution of topics. Rabinowitz *et al.* (1993) discovered of belt of small Earth-approaching asteroids (SEAs) and postulated a lunar source for these objects. While studying this problem, it was determined that although some facets of the orbital distribution of the SEAs could be explained using the lunar source, the required number of large (≥ 10 m) meteoroids could not be launched without having the number of lunar meteorites be far larger than observed. It was then natural to study the delivery dynamics of these lunar meteorites, and then extend this to include the martian ones as well.

Brett accepted the offer of a Henri Poincaré fellowship to work at l'Observatoire de la Côte d'Azur in Nice, France, to begin Sept. 1, 1996. He will then begin a post-doctoral fellowship at the Canadian Institute of Theoretical Astrophysics in Toronto, Canada on Sept. 1 1997.

To my family, for their support,
to Sue Chamberlain, for making writing this less painful,
to George Wetherill, for whom I have the greatest respect,
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to Joe Burns, for his guidance.

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Joe Burns receives my utmost appreciation for the support he has given me throughout my time at Cornell. Joe allowed me free reign to pursue topics that attracted my interest, and was a source of sage advice in every case. His abilities as an editor are second to none, and I believe that my ability to concisely express scientific ideas has increased greatly under his tutelage. The opportunities he provided for travel to conferences allowed me to meet and collaborate with many scientists; I believe that this has helped my career immensely. I regret that we were never able to make the mythic journey to Palomar together.

I learned much from Phil Nicholson in the course of one class and many discussions. Phil encouraged me to be a better scientist by stressing the importance of having facts at one's fingertips so that ideas can be quickly checked for sanity. His thorough reading of this thesis has resulted in several improvements.

Martha Haynes, Terry Herter, Tyler Nordgren, Phil Nicholson, and Marco Scodeggio, were of great help in preparing for trips to Palomar. Greg Black, Tyler Nordgren, Marco Scodeggio, and Peter Wilson were receptive to hearing me attempt to explain some idea or another that I'd gotten into my head, and crucial in helping to get through those first-year electrodynamics and statistical mechanics problem sets during our weekend homework-crunching meetings. Dane Quinn and Richard Rand were a pleasure to work with on the satellite-spin problem, and I learned a great deal of non-linear dynamics from Richard and Philip Holmes (how much I remember off the top of my head is another story of course...).

Martin Duncan and Hal Levison were very kind in providing me with their numerical integration code (RMVS), without which this thesis would not have been possible. Joe Burns must be commended for allowing me talk him into purchasing a fast Hewlett Packard workstation, which made this study feasible.

George Wetherill and Paul Warren provided a wealth of creative ideas and thoughtful criticisms at various stages of this work. Many of the ideas behind this thesis follow directly from Paul's work. I have the utmost respect for George Wetherill, whom I view as the father of this whole field; I shall not soon forget his wisdom and his insight.

Sue Pakkala, Danielle O'Conner, Sandy Mack, and Elizabeth Bilson all helped me by taking care of the nitty-gritty details of everyday existence, and photocopying all those papers. I especially must express my gratitude to Cheryl Hall for her unwavering, smiling assistance in all manner of deeds relating to paper submissions, faxes, 4:59 PM Fed Exs, and mailing out preprint after preprint (but man, how I loved that 'printed matter' stamp!).

On the social front, I thank Matt Ashby for his priceless support as a friend through good times and bad; never have I felt that someone understood me so well. Amy Miran brightened many an hour with her good humor and her menagerie. I will remember fondly all the trips with Tyler Nordgren and Julie Rathbun to various watering holes. Marco Scodeggio and Anna Giuliani provided many an enjoyable get-together; unforgettable dinners were provided by Anna's skilled hands (one word: gnocchi!). I was fortunate enough to be graciously entertained in the sumptuous kitchen-by-the-lake of Joseph and Judy Burns on several occasions. Martha Haynes and Riccardo Giovanelli hosted memorable evenings at their house. Many a fine steak (rare, of course) was devoured at the secretive bi-annual meetings of the MEA (Meat-Eaters Anonymous, founded by myself, Tyler, and Riccardo). To this day I wonder: does Martha know?

Treasured memories of Ithaca include: Bound for Glory (a live Sunday night folk music broadcast), sailing on Cayuga Lake, a tasty beer or two at the Chapter house, those wonderful wine-tasting expeditions, gorge hiking, plays at the Hangar Theater, dancing with Donna the Buffalo, Sunday morning coffee on the Ithaca Commons with Matt and Tyler, picnic-table lunches at the Big Red Barn with the Space Sciences gang, night skiing at Greek Peak, yummy bagels at CTB, picnics in Stewart Park, the Ithaca Festival, the wine club, and of course those incredible autumn colors.

My parents have always stood behind me, and their continuous assistance was invaluable. Lastly, I am grateful to Susan Chamberlain for her help and support while this thesis was being written. Sue made every one of my last days here at Cornell enjoyable, even during the worst stress. My heartfelt thanks Sue.

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