Book Review

Fly Me to the Moon

Reviewed by Shane Ross

Fly Me to the Moon
Edward Belbruno
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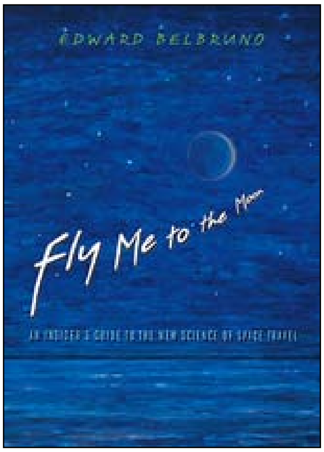
There is a revolution afoot in how space travel is done. Forget the big rocket burns of the past, which sent spacecraft hurtling away from Earth only to need more large rocket burns to slow them down and enter orbit at their destination, be it the Moon, Mars, or beyond. Think instead of comets, wise old travelers of the solar system, which follow the complex interplay of gravitational forces to move from one place to another, sometimes finding themselves in a temporary orbit around a planet. While we can't (yet) influence the motion of comets, we can learn lessons from them as to how we can control spacecraft, directing them in such a way that they travel vast distances and get captured around planets and moons using practically no fuel.

Edward Belbruno's *Fly Me to the Moon* provides an insider's look at this revolution, what the subtitle calls "the new science of space travel". The book intermingles popular-level explanations of some new and fascinating concepts regarding gravity, chaos, and spacecraft trajectory design with the interesting personal story of Belbruno's moments of discovery and struggle. The book provides excellent, readily accessible, and profusely illustrated examples of the uses of chaotic dynamics in celestial mechanics. And Belbruno's story provides insight into how new ideas gain acceptance within the scientific and engineering communities, sometimes at great personal cost to the proponents.



The setting of celestial mechanics provides a seemingly timeless context that conjures up images of famous regularity, the clockwork cosmos of circles within circles. But that's only when one considers the two-body problem of a spacecraft and only one massive body at a time. Belbruno infuses the element of chaos by adding one more massive body to the mix and considering the three-body problem, for example a spacecraft moving in the Earth-Moon system. By "chaos", Belbruno is referring to sensitive dependence on initial conditions. The motion of an object is considered chaotic "if a tiny change in the motion at some moment results in a large change [in] the motion of the object and a substantially different trajectory."

To help us visualize the chaotic motion of the third (and smallest) body in a three-body system, Belbruno introduces the concept of a "weak stability boundary" around one of the larger, massive bodies. Take the Moon, for example. The weak stability boundary of the Moon is a set of locations where the gravitational attraction of the Moon is almost balanced by the attraction of the Earth. This boundary is a separatrix in the phase space, a critical surface where a

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spacecraft is particularly sensitive to perturbations. A slight jostle one way or the other and the spacecraft heads off to very different fates, either falling toward the Moon or hurtling away from it. On the boundary itself, however, a spacecraft is weakly captured in a kind of celestial limbo. But with a small rocket maneuver, a weakly captured spacecraft can be placed on a stable orbit around the Moon. If trajectories can be found from Earth to the Moon's weak stability boundary, these routes could potentially be very useful in practical applications as a cheaper (if not the cheapest!) way to the Moon.

Throughout the book, Belbruno leads us through the professional and mental trajectory he took to arrive at the weak stability boundary, its uses, and its myriad insights. Through personal accounts, a picture is painted of a man uniquely suited to tackling an interesting problem. Leaving an assistant professorship post in a mathematics department, in 1985 Belbruno headed to NASA's Jet Propulsion Laboratory in California, in search of "some new ideas, often not easy in an academic setting in which one has to pay attention to what is acceptable or trendy at the time." This gives us a glimpse of what motivated Belbruno, but more generally what motivates all good and lasting mathematics research: a dedication to the discovery of timeless truth, independent of the momentary and ever-changing winds of fad and research dollars.

In a new position as a trajectory mission analyst, Belbruno found himself wondering if it were possible to find a path through space that, after an initial boost near Earth, could get a spacecraft captured by the Moon using no fuel (sometimes called a "ballistic capture"). This would be analogous to standing on a beach in Florida and throwing a bottle into the ocean, into just the right current and at just the right time, so the bottle washes ashore in France. The ballistic capture concept was a far cry from the trajectories used by missions like Apollo, which were moving so fast relative to the Moon when they approached it that another large expenditure of fuel was necessary to get into lunar orbit. If a ballistic capture path could be found, it could dramatically reduce the cost of a mission.

After asking around and searching the literature, Belbruno found that in the 1960s Charles Conley conjectured that ballistic capture trajectories from the Earth to the Moon might exist, but Conley never found them. Belbruno had a hunch they did indeed exist and was determined to find them. Much of the book discusses both the theory and the personal story of how he did find them.

The first success came in 1986. Using his concept of the weak stability boundary, Belbruno found a low-fuel trajectory using ballistic (or weak) capture for the Lunar Get Away Special (LGAS) mission. The LGAS mission went through planning stages but never flew. However, the European Space Agency's SMART 1 mission to the Moon, which launched in 2003 and arrived at the Moon in 2004, was inspired by the LGAS design—a vindication of that initial discovery.

The most spectacular success of Belbruno's weak stability approach was in the rescue of a Japanese mission to the Moon. The mission originally had two spacecraft, MUSES-A and MUSES-B; B was to go into orbit around the Moon, with A remaining in Earth orbit as a communications relay. But B failed, and A did not have sufficient fuel to make the journey to the Moon by the conventional route planned for B. However, by utilizing the ballistic capture concept, Belbruno and colleague James Miller found a way to get A to the Moon that fit within the fuel budget. MUSES-A (renamed Hiten) left Earth orbit in April 1991 and reached the Moon that October, making it the first ballistic capture trajectory to actually fly. As a result, Japan became the third nation to send a spacecraft to the Moon.

As Belbruno shares, his ballistic capture approach was not appreciated by many of his colleagues at the time. The trajectory flight times were long, and the idea of using chaos to design a trajectory conjured images of unpredictability that were not consistent with the way trajectories had previously been designed. The idea of using "chaos to guide a spacecraft to the Moon and have it achieve orbit with no fuel" was "the shattering of a paradigm". And paradigms, bulwarked by the human tendency to depend on the tried and true, do not like being shattered.

The book begins by considering spacecraft trajectories, but goes on to describe an entire zoo of strange orbital behaviors and their significance for natural objects. For example, while studying chaotic motion of small objects, or rocks, in the Earth-Moon system, Belbruno found interesting cases of intermittent behavior wherein the rock would perform peculiar resonance transitions. The rock would start out in an orbit around the Earth that was beyond the Moon's, but in resonance with the Moon's orbit. After passing closely by the Moon, the rock would then get into an Earth orbit interior to the Moon's, and also in resonance. This kind of resonance transition had not been observed before, and Belbruno linked it with weak stability boundaries. Interestingly, Belbruno relays how the same behavior has been seen among comets under the sway of Jupiter's weak stability boundary. During encounters with Jupiter, some comets loosely orbit the planet, becoming temporarily captured moons. Analogous behavior has been seen in Kuiper belt objects, large comet-like objects that interact strongly with Neptune. Also intriguing is the possibility of near-Earth objects that are caught in a chaotic tangle related to the Earth's weak stability boundary. Belbruno speculates that perhaps the large impactor that collided with Earth to form the

Moon was in this precarious dynamical situation some four billion years ago.

The principles of the weak stability boundary are not limited in scale, being a general feature of the three- (or more) body problem. Near the end of the book, Belbruno discusses recent work on comets moving between the stars. These interstellar wanderers get temporarily captured at a star before moving on to the next. These are of course slow processes. Nevertheless hitchhiking the galaxy from star system to star system may in fact take place, albeit on very large time scales. Belbruno points out the implication for life-bearing material hitchhiking on interstellar comets, which may collide with a planet while temporarily captured around a star. This mechanism may provide "a key to the origin of life within our own solar system."

Fly Me to the Moon provides a fast, very readable account of new developments in chaotic celestial mechanics, especially low-fuel space travel, at a level appropriate for a general audience. By the end, nonmathematicians will have gained some intuition about one of the hallmarks of chaos, sensitive dependence on initial conditions, and how chaos can be harnessed to good purpose. All readers will walk away thinking differently about the cosmos. Far from being a clockwork, it will seem more dynamic, more turbulent, and full of diverse possibilities.