

Did Celestial Chaos Kill the Dinosaurs?

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1. Introduction and Motivation

I'd like to talk to you today about an overarching theme of the astro- & geosciences: from the stars & planets to the sediments we tread on & the dragons who are no longer with us. The issues we'll discuss include the stability of the Solar System, a classical problem of mechanics, if ever there was one.

As many of you know, there is lots of news since Poincaré pointed out the mathematical difficulties of the many-body problem and since KAM (Kolmogorov-Arnol'd-Moser) theory overcame some of these difficulties. Some of you also know that KAM theory — with its beautiful invariant tori and the quasi-periodic motions that they support — while largely motivated by celestial mechanics, doesn't really apply to the stability of the Solar System. On the contrary, recent numerical calculations have demonstrated that there is chaos, chaos everywhere in the Solar System, among the planets, as well as the asteroids.

My motivation for today's talk is largely provided by the availability of new tools — analytical and numerical, namely Lie-series averaging & “digital orreries,” respectively — to study the governing ordinary differential equations of celestial mechanics. I will illustrate their use by discussing three sets of results that essentially span my career in this field: (i) a unified theory of groups and gaps in the asteroid belt; (ii) a novel source of robust chaos in the motion of the outer planets; and (iii) last but not least, the result that provides the title of this lecture, namely changes in the behavior of the planetary motions at 65 My (million years) before present (B.P.).

My talk is based on joint work with Bill Kaula (UCLA, R.I.P.), Bruce Runnegar (Earth & Space Sciences Dept. and the Institute of Geophysics & Planetary Physics -- IGPP, at UCLA + the NASA Astrobiology Institute -- NAI, at the NASA Ames Research Center), Ferenc Varadi (IGPP + Physics & Astronomy Dept., UCLA), and Gershon Wolansky (Mathematics Dept., Technion--Israel Institute of Technology). I would like to dedicate it to Bill, a wonderful person and great contributor to the planetary sciences. The single most important contributor to the work covered by the talk was Ferenc, to whom go my heartfelt thanks for a collaboration that extends over more than 15 years.

2. Groups and gaps in the asteroid belt

The asteroid belt lies between the orbits of Mars and Jupiter and its combined mass equals roughly that of a terrestrial planet; the semi-major axes of these two planets equal approximately 1.5 and 5.2 AU (astronomical unit = mean Sun–Earth distance). The distribution of the number (or mass) of asteroids as a function of semi-major axis is very inhomogeneous, as shown in Figure 1.

An abiding mystery of this distribution is the contradictory role played by mean-motion resonances. In the inner belt, closer to Mars, there are large “gaps”, i.e.

minima in the number of asteroids near certain resonances; see the 4:1, 3:1 and 5:2 resonances, for instance. These gaps are often called the Kirkwood gaps, after the author of a classic book on them (1867). In the outer belt, closer to Jupiter, where the overall number of asteroids is much smaller, certain resonances show an excess over the surrounding mean distribution. The most famous one is populated by the Trojans, in 1:1 resonance with Jupiter, followed by the Hildas, at 3:2.

There is a rich literature on explaining these gaps and groups, many papers being dedicated to the study of individual resonances. Thus the work of Jack Wisdom explained the 3:1 gap by the resonance inducing chaos in the motion of an asteroid at that orbital position, which presumably leads to ejection from it.

Our approach to solving the paradox of groups and gaps was to include small dissipation in the restricted three-body problem, in which an asteroid is merely a test particle in the variable force field induced by the motion of the Sun and Jupiter. As a first approximation, it is quite common in computing the motion of asteroids to neglect the effects of Mars, which is much smaller, and of Saturn, which is much farther than Jupiter. The idea in our approach is that the asteroids formed in the primordial dust cloud around the Sun, from which only Jupiter had emerged.

We formulated a model for the effect of elastic dust-particle collisions with a spherical asteroid and added this effect to the Hamiltonian equations governing the planar restricted three-body problem. Given certain reasonable assumptions about the density distribution of the primeval disk, we obtained trapping into or breaking away from resonances, via a decrease or an increase in the asteroid's eccentricity, respectively; the former seems to be likelier in the outer belt, the latter in the inner belt.

3. Robust planetary chaos

Over the last two decades, a combination of ingenious coordinate transformations and careful, extended numerical integrations has demonstrated that the Solar System exhibits certain characteristics of chaotic behavior. Most strikingly, Jacques Laskar in France and Jack Wisdom and his associates in the USA have shown that the leading Lyapunov exponent computed from multi-million year integrations of the governing equations is positive, i.e., that small perturbations in the position of the planets at any moment will grow in time. This exponential divergence of trajectories, however, should not perturb our sleep (pun intended, of course), since the associated instabilities seem to saturate rapidly and the chaotic component of the motion stays small: no catastrophic events occur, even in the longest integrations of these authors, the orbits of the planets remain separated, and none is ejected from the Solar System.

The above-mentioned seminal work ignored, however, a well-known difficulty in studying the secular behavior of the system, i.e., the behavior of the planetary orbits after averaging out the revolution of each planet around the Sun. This difficulty is associated with the so-called "Great Inequality," the quaint name given in celestial mechanics to the 2:5 near-resonance between the mean motions of Jupiter and Saturn. Since these two are the most massive planets in the system and lie in its very midst, the effect of this resonance had been shown half-a-century ago, by Brouwer and others, to be of considerable importance.

Analytic results on the Sun–Jupiter–Saturn system led us to suspect the importance of the Great Inequality in contributing to chaos in the full Solar System. Our predecessors concentrated on very long integrations, 100 My and longer, of as good an approximation of the actual masses and positions of the planets as they could obtain. But a positive Lyapunov exponent is only a symptom of chaos, not an explanation.

We proceeded to study the causes of chaotic behavior in the outer Solar System by the systematic approach of bifurcation theory. In this approach, the behavior of a dynamical system is studied by varying a parameter of the system and following changes in its behavior, from the simple to the more complex. This allows one to discover the instabilities that give rise to the complex behavior.

The parameter we chose is the eccentricity of Saturn. By varying this orbital parameter by a few permil (one tenth of 1 percent), we carried out hundreds of integrations of roughly 10 My, using either 2 (Jupiter and Saturn) or 4 (these plus Uranus and Neptune) outer planets. The main frequency that changes when changing this parameter is that associated with secular variations in Saturn's orbit (g_6 in the usual terminology), while that associated with Jupiter (g_5) stays fairly constant. As a result, the critical period associated with the beats of the Great Inequality increases from about 1000 years to 2000 years and longer. When the beat period exceeds about 2000 years, chaotic behavior ensues in our integrations.

This chaotic behavior is robust with respect to changes in other parameters and the initial state of the system, as well as the presence of 2 or 4 planets. The exponential divergence of trajectories corresponds to a Lyapunov time (inverse Lyapunov exponent) of about 20 Kyr, much shorter than in the integrations of Laskar, Wisdom and associates. We conclude that the Solar System is likely to have experienced intervals of vigorous chaos during its slow evolution from primeval disk to the current state.

4. Sling-shot asteroids

We have addressed so far the trapping and ejection of asteroids due to resonances with Jupiter's motion, as well as changes in the behavior of the major planets as the orbital parameters of one of them change. It is time to bring these two ingredients together and address the question in the title of this talk.

To do so, we have carried out a very detailed study of the Solar System on the time scale of 100 My into the past, as well as into the future. Both changes in physical model — such as various ways of taking into account the Earth–Moon system or the moment of inertia of the Sun — and in the numerical method (such as step size) were investigated. We believe therefore that the results using our best model are quite reliable over about 70 My, both forward and backward in time.

These results clearly show, at least for certain parameter values, a change in the overall character of the motion of certain planets at 65 My B.P., as well as at about 30 My in the future. The former “regime change” provides a striking, and maybe fortuitous, coincidence with the Cretaceous–Tertiary boundary and its major extinction event.

We have carried out accordingly a large number of simulations of the motion of specific asteroids in the “chaotic sky” provided by the time-varying force field of the major planets in the above-mentioned results. These test-particle simulations indicate the presence of numerous intriguing jumps in their orbital parameters. Such jumps are likely to lead to ejection from the asteroid belt and subsequent Earth-orbit encounters. We haven’t caught the culprit that presumably fell into the Yucatan peninsula yet. But if we do, I’ll make sure to come back and report it.

Acknowledgements. It is a pleasure to thank you, my new colleagues in the Royal Astronomical Society, for electing me as an Associate. The citation mentioned my “work in the fields of geophysical fluid dynamics, climate dynamics and physical oceanography.” But joining you at the present Annual Meeting provided me with this great opportunity of looking back on my celestial mechanics “hobby,” acquired while first a student and then a faculty member at the Courant Institute of Mathematical Sciences in New York City, where Jürgen Moser (of KAM fame) was one of the great teachers I encountered.

There is another great debt I’d like to acknowledge here, and that is to Jay Fein, my program monitor over many years at the National Science Foundation. Jay not only tolerated, he even encouraged such hobbies, which sometimes did turn into contributions of substantial relevance to his Climate Dynamics Program.

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Figure 1. Distribution of the number of asteroids, as a function of their distance from the Sun; the semi-major axes are normalized by that of Jupiter (not that of Earth). Notice the gaps in the inner belt and the groups in the outer belt.

Number of Asteroids

