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THE EARTH-MOON SYSTEM AND THE DYNAMICAL STABILITY OF THE INNER SOLAR SYSTEM

KIMMO INNANEN
Department of Physics and Astronomy, York University, 4700 Keele Street, Toronto, ON M3J 1P3, Canada
SEPPO MIKKOLA
Tuorla Observatory, University of Turku, 21500 Piikkiö, Finland
AND
PAUL WIEGERT
Department of Physics and Astronomy, York University, 4700 Keele Street, Toronto, ON M3J 1P3, Canada
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ABSTRACT

Evidence from self-consistent solar system n-body simulations is presented to argue that the Earth-Moon system (EM) plays an important dynamical role in the inner solar system, stabilizing the orbits of Venus and Mercury by suppressing a strong secular resonance of period 8.1 Myr near Venus's heliocentric distance. The EM thus appears to play a kind of "gravitational keystone" role in the terrestrial precinct, for without it, the orbits of Venus and Mercury become immediately destabilized. The mechanism of the resonance, driven by the giant planets, is described. Approximate limits are provided for the mass and heliocentric distance required of EM to perform this role, and results from several additional empirical tests are reported. A number of avenues of further investigation are suggested.

Key words: celestial mechanics, stellar dynamics — Earth — Moon — solar system: general

1. INTRODUCTION

The classical problem of the long-term stability of the solar system continues to motivate, challenge, and perplex dynamicists. Answers to the old questions regarding the uniqueness of the semimajor axes and masses of the planets still seem distant and elusive. Nevertheless, contemporary developments in computing power, data storage, and fast, efficient numerical algorithms are making new insights possible. In addition, observations of circumstellar disks, together with dark, "planet-like" companions orbiting some nearby stars, provide additional impetus for continuing work on the solar system as a prototypical planetary system. A great amount of recent research has emphasized the transport of interplanetary "debris" from the outer to the inner parts of the solar sytem (Milani, di Martino, & Cellino 1994; Mikkola & Innanen 1984). A contemporary review has been given by Duncan & Quinn (1993). Studies relating to the Kuiper belt are by now a small industry.

Although the configuration of the giant planets can be considered stable in the gigayear time frame, there has emerged a consensus that the orbits of the terrestrial planets and Pluto are, at the least, in the neighborhood of dynamical chaos (Laskar 1990; Laskar, Quinn, & Tremaine 1992). This chaos arises from the presence of various long-period secular resonances in the solar system, with e-folding timescales in the tens and hundreds of millions of years. Laskar (1994) has stressed the importance of large-scale chaos and secular resonances in the inner planets' system. It is worth remembering that dynamical chaos should not be construed as a threat to the long-term overall physical stability of the solar system, but rather as an indication that accurate prediction of planetary positions and velocities beyond these timescales is unreliable, because of sensitivity to starting conditions.

Here we provide evidence from numerical simulations that the Earth-Moon system (EM) evidently plays a crucial role in the long-term stability of the terrestrial planetary orbits: without the presence of a significant (at least Mars-like) mass in the neighborhood of the EM heliocentric distance, the orbits of Venus and Mercury are immediately exposed to one or more strong, destabilizing secular resonances concerted by the giant planets.

In this context, we mention the pioneering work of S. J. Aarseth (unpublished), wherein he detected hints of analogous results. In what follows, various numerical simulations are described that illustrate these conclusions, the probable causes are identified, and several interesting avenues for future investigation are mentioned.

2. METHOD AND SIMULATIONS

Our original results arose in a rather serendipitous manner, as S. M. and K. I. were testing the relative merits of several n-body integrators. We basically were checking to see whether anything changed when one or more of the terrestrial planets was removed from the system. A great deal of subsequent testing by different methods (and by others) has shown that these results are clearly not numerical artifacts of an integration method. Consequently, the following results are all based on the now well-known and efficient Wisdom-Holman symplectic mapping method (Wisdom & Holman 1991). The barycenter of EM has been used, and Pluto has not been included in our simulations.

We begin with the finding that removing Mercury or Mars from the simulation produced no discernible changes in the million-year time frame. We will return to a comment on Mars later. Removing Venus from the simulation causes the orbits of EM and Mars to become more regular as functions of time, but no significant secular changes were seen.

Interesting results were observed *immediately*, however, when EM was removed from the simulations. These results are now described in three stages, with and without Mercury, and with test particles only in the terrestrial precinct. Mars and the giant planets were retained, of course.

1. *Without Mercury.*—It has been routine in many simulations to try to avoid numerical problems that arise from

Mercury's rapid motion. This is accomplished simply by putting Mercury's mass into the Sun. Our first result follows this plan. Thus, in Figure 1 we show the time behavior of Venus's orbital eccentricity when EM has been removed, and Mercury placed into the Sun. The result is immediate and dramatic. The Venusian orbital eccentricity increases to a maximum near 0.6, and continues to vary with that amplitude, with a period of about 8.1 Myr. No concurrent significant change takes place in Venus's semimajor axis.

2. *With Mercury.*—In this case, over an initial time period of several Myr, the Venusian eccentricity shows a modest periodic fluctuation, but remains less than 0.1; but now one observes dramatic changes in Mercury's orbital eccentricity, at times exceeding 0.7, as shown in Figure 2. This state of affairs must *inevitably* lead to a powerful encounter between Venus and Mercury, probably leading to Mercury's ejection. We have not rehearsed the details of such a scenario at this time. Once Mercury has departed, the behavior of Venus's eccentricity described in point 1 must ensue. These results tend to confirm, in a somewhat different way, Laskar's (1997) conclusion that even in their present configuration, chaotic diffusion in the terrestrial precinct could allow for a strong Mercury-Venus encounter.

3. *Test particles only in the terrestrial precinct.*—To shed more insight into what is happening here, we removed *all* of the terrestrial planets from the simulation and " seeded " the terrestrial precinct with several hundred massless test particles in nearly round orbits. Their behavior is shown in Figure 3, successively adding Saturn, Uranus, and Neptune to Jupiter in the simulations. We observe dramatic increases in the test-particle eccentricities very nearly at the distance of Venus, and progressive strengthening of the effect as the giant planets are added. This system, with only the giant planets in it, reveals the result that these planets are orchestrating some sort of secular resonance very near the heliocentric distance of Venus. We find that the longitude of Venus's perihelion librates with the longitude of Jupiter's perihelion; if the semimajor axis is less then the Venusian value, the perihelion longitude rotates in the opposite direction with respect to Jupiter's perihelion longitude than if the semimajor axis is larger than that of Venus. At Venus's semimajor axis, there is a secular resonance; it is a narrow, but still finite, zone of libration. Although Jupiter is the main agent for this resonance, the other giant planets clearly function so as to reinforce the effect. It should be emphasized that this particular test-particle simulation is intended only as a *diagnostic* test for resonances to permit proper identification of the source(s) of the resonances. Beyond that, it has no other physical significance.

We next examined the questions of how critical are the semimajor axis and mass of EM, so that stability can be maintained. Here we find that a mass of some 10% of EM restores stable behavior, at least in the 10 Myr time frame, and that this " threshold " mass of EM should have a semimajor axis within 10% of 1 AU. These values have been

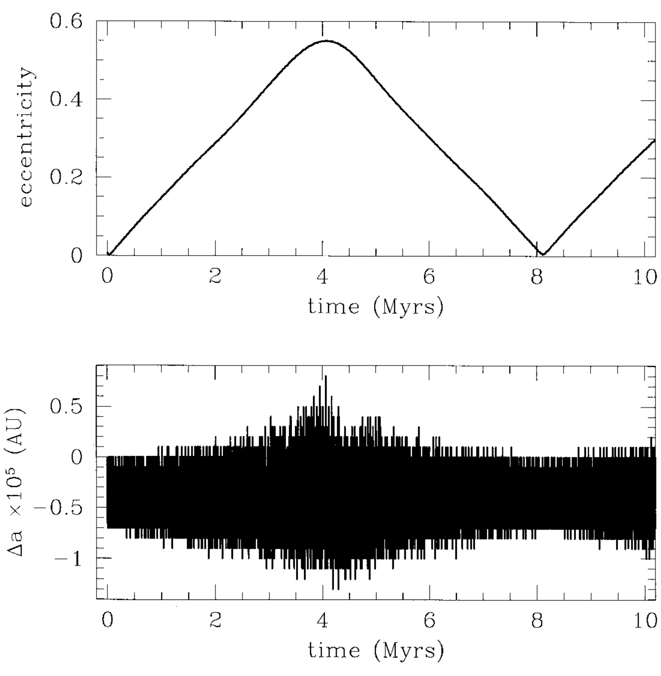

FIG. 1.—Venus's eccentricity and the change in its semimajor axis in a solar system model that does not include Mercury or the EM.

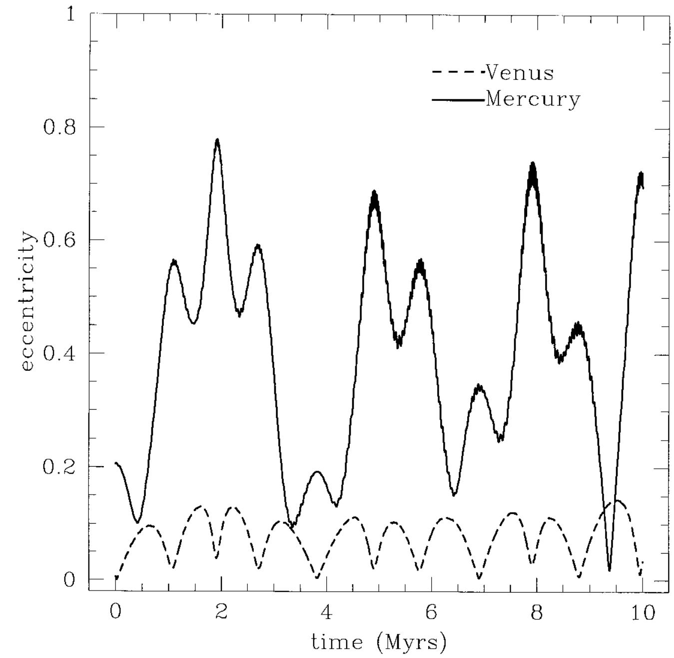

FIG. 2.—Evolution of Mercury's and Venus's eccentricity in a solar system model that does not include EM.

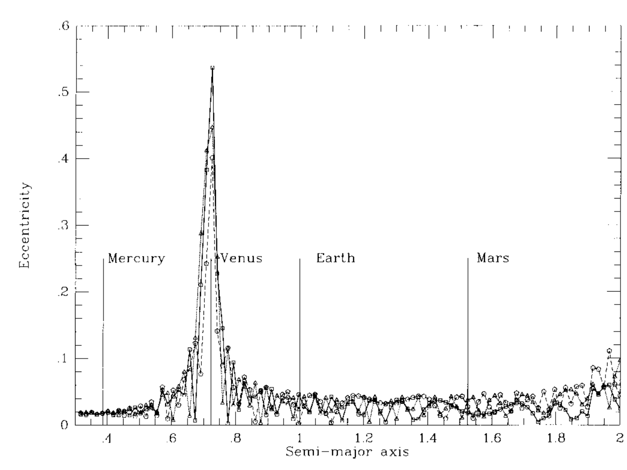

FIG. 3.—Eccentricities of test particles in the terrestrial region in a model solar system including only the sun and the giant planets. Triangles are measured at 3 Myr, squares at 4 Myr, and pentagons at 5 Myr.

determined by trial and error. That the semimajor axis of EM is not too critical (at least in the 10 Myr time frame) can also be shown semianalytically, by uniformly distributing the threshold EM potential, as averaged over one period at various heliocentric distances near 1 AU. Thus, at least a Mars-like mass in the neighborhood of the EM position is essential for long-term stability of the orbits of Mercury and Venus. One must fully acknowledge that the presence of additional unknown resonances on much longer timescales may yet require further refinements of these values.

The possible activity of relativistic effects in our simulations has been checked in an ad hoc manner. We simply added the standard relativistic correction terms to the terrestrial planets in one of our simulations. Those effects did not affect our conclusions in any significant way.

Mars seems to be a relatively independent presence in our experiments. We find the onset of significant changes only if Mars's mass were significantly to exceed the (normal) EM mass. We have not examined this question thoroughly in this work, recognizing, among other matters, that Mars's environment is strongly influenced by Jupiter.

3. CONCLUSIONS

First, we find that EM is performing an essential dynamical role by suppressing or "damping out" a secular resonance driven by the giant planets near the Venusian heliocentric distance. The source of the resonance is a libration of the Jovian longitude of perihelion with the Venusian perihelion longitude. As far as we know, this is the first evidence of such a phenomenon in the solar system. One seems to require, at minimum, a Mars-like mass in the EM neighborhood to perform this essential task. That Venus should exist very close to the exact heliocentric distance of this resonance may, perhaps, be just a coincidence. We think not, but agree that further testing is needed to see how much this resonance can be shifted. The results invite a number of interesting cosmogonic questions for which no answers can be given at this time. It is also interesting that Mercury's orbit is coupled to that of Venus. The results seem to hint at some sort of dynamical relationship between these two planets. This question we also leave to future work. Whether or not the stabilizing role of EM in the resonance has other effects on the relationship between EM, Venus, and Mercury, we consider to be beyond the scope of this paper. Our basic finding is nevertheless an indication of the need for some sort of rudimentary "design" in the solar system to ensure long-term stability. One possible aspect of such "design" is that long-term stability may require that the terrestrial orbits require a degree of irregularity to "stir" certain resonances enough so that such resonances cannot persist. It will certainly be of interest to revisit soon the enigma of the 5:1 synchronous relationship between Venus's (retrograde) spin and its synodic relationship to EM (e.g., Chaisson & McMillan 1996, p. 198). Perhaps some as yet unidentified resonant linkage is at work here. Of course Venus's low-spin angular momentum and lack of natural satellites also remain outstanding questions in their own right. These comments may not be just pure conjecture: it is appropriate in this context to mention the interesting results found recently by Forte & Mitrovica (1997), where the main perturbation frequency of Earth's precession is shown to be related to a secular term in the orbits of Jupiter and Saturn. They have provided an alternative mechanism (evolution of the tectonic plates) to achieve a resonance analogous to one investigated earlier by Laskar, Joutel, & Boudin (1993).

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