Mem. S.A.It. Vol. 80, 301

Memorie della

Recent advances in Solar System dynamics

G. B. Valsecchi

INAF – IASF-Roma, via Fosso del Cavaliere 100, I-00133 Roma, Italy
e-mail: giovanni@iasf-roma.inaf.it

Abstract. Recent years have seen a dramatic increase of our knowledge of how large and small Solar System bodies move.

Key words. Solar system: general – Chaos

1. Introduction

The attempt to understand and predict the motions of major Solar System bodies has been the main driver for the birth and the development of science; in particular, the lunar problem has played a fundamental role in this context (Gutzwiller 1998).

For centuries the apparently immutable planetary motions have instilled in the minds of researchers the idea of an ordered universe, in which planets and satellites move on stable and predictable orbits and the only unpredictable events are the rare apparitions of comets.

That the latter move on chaotic orbits became clear after the analyses of Lexell (1778) and LeVerrier (1857) of the motion of comet D/1770 L1 Lexell, due to the planetary close encounters that this comet underwent in the XVIII century.

However, chaotic motions are far more widespread than one would have imagined; this is a rather more recent achievement, and hereafter we are going to mention recent results that illustrate this. The list is, of course, far from exhaustive, and may be used as a starting point to explore the vast recent literature on Solar System dynamics.

Send offprint requests to: G. B. Valsecchi

2. Dynamics of the planets

2.1. Slow chaos in planetary motions

Planetary motions have been shown to be weakly chaotic by Laskar (1989), using numerical integrations of the averaged equations of motion; more recently, Laskar (2008) has investigated, also by direct integration of the non-averaged equations, the role of general relativity.

2.2. Chaotic spins of the inner planets

Laskar and Robutel (1993) have shown that secular planetary perturbations are able to induce large, chaotic variations of the spin axis orientations of terrestrial planets. For Mercury and Venus, solar dissipation has had a stabilizing effect, while the obliquity of Mars is still largely chaotic. Also the Earth could have a chaotic spin axis orientation, were it not for the presence of the Moon (Laskar et al. 1993).

2.3. The Nice model

Tsiganis et al. (2005) have hypothesized that, if the giant planets formed in less eccentric and less inclined orbits than those that they currently occupy, the passage of Jupiter and Saturn through their 1:2 mean motion resonance could have led to an abrupt change of orbital configuration, affecting the entire system. The strong point of this scenario is that it makes quantitative predictions concerning the orbits of some small body populations like the Trojans (Morbidelli et al. 2005), and on the circumstances of occurrence of the Late Heavy Bombardment (Gomes et al. 2005); these predictions are the subject of ongoing research.

2.4. Reconstruction of past Earth insolation

Notwithstanding the weak chaos present in the planetary orbits, Laskar et al. (2004) have been able to reconstruct the past insolation of the Earth over many tens of millions of years, with excellent agreement with the available paleoclimatic data.

3. Dynamics of the satellites

3.1. Many new irregular satellites of the giant planets

The number of satellites of the giant planets has increased dramatically in the last 30 years; the majority of the recent discoveries are "irregular satellites", for which solar perturbations play a major rôle, and whose origin is far from clarified (Jewitt and Haghighipour 2007).

3.2. Dwarf planet and asteroid satellites

The presence of satellites is by no means a prerogative of planets: asteroids, including Near-Earth Asteroids (NEAs) have satellites (Merline et al. 2002); the presence of satellites is widespread throughout the various populations of small Solar System bodies (Noll 2006). Of particular interest is their presence around trans-Neptunians and dwarf planets (Noll et al. 2008).

3.3. Heating of regular satellites through resonance couplings

One of the major discoveries made by Voyager 1 at Jupiter, the volcanism of Io, had actually been predicted: Peale et al. (1979) showed that the forced eccentricity associated with the Laplace resonance, coupled with the Jovian tides raised on the satellite, would have melted a major fraction of the mass of Io. Peale (1999) discussed how dissipation of tidal energy in some satellites can affect orbital and spin configurations, and could affect their interiors.

4. Asteroid dynamics

4.1. Incredible amount of accurate astrometric and orbital data

The increasing interest in NEAs has led to the implementation of very successful NEA telescopic surveys (Larson 2007) that, as a by-product, have increased by orders of magnitudes the number of asteroids for which we have reliable orbital information. Further advances in this field will result when the future generation surveys will come on line (Jedicke et al. 2007), (Ivezić et al. 2007).

4.2. Slow chaos everywhere in the Main Belt and in many zones of the trans-Neptunian region

Guzzo and Morbidelli (1996) showed that modern results of the theory of dynamical systems can be applied to study the confinement of asteroids in some regions of the asteroid main belt; the diffusion of orbits in the main belt is reviewed by Nesvorný et al. (2002a). Morbidelli (1997) studied the chaotic diffusion in the trans-Neptunian belt.

4.3. Identification of young families

Nesvorný et al. (2002b) were able to identify, purely on dynamical grounds, a family-forming collision in the asteroid belt that took place about 5.8 million years ago. After this important result, numerous further events of this type have been found (Nesvorný and Vokrouhlický 2006).

4.4. Non gravitational forces (meteorite delivery, spin distributions)

Rubincam (1995) and Farinella et al. (1998) showed that the motion of small bodies can be significantly affected by a non gravitational effect, first described by Yarkovsky; the implications can be significant for the delivery of meteorites to the Earth. Thanks to accurate radar astrometry at multiple apparitions, Chesley et al. (2003) were able to detect and measure this effect on a small NEA, while Vokrouhlický et al. (2008) were able to identify old observations of another NEA using a dynamical model including the Yarkovsky effect, without which the identification would not have been possible. The related YORP effect has been shown by Rubincam (2000) to have important consequences on the spin of small asteroids.

4.5. Near-Earth Asteroids (NEAs)

This is a rapidly expanding field, as attested by the recent IAU Symposium dedicated to it (Milani et al. 2007). Of particular relevance to dynamics is the recent implementation of algorithms that allow to identify even very low probability collision possibilities of newly discovered NEAs with the Earth (Milani et al. 1999). In fact, automatic software robots have been implemented to perform this task (Milani et al. 2005), while theoretical understanding of the dynamics leading to collisions has also progressed (Valsecchi et al. 2003).

5. Comet dynamics

5.1. Centaurs, the dynamical link between Jupiter family comets and the trans-Neptunian region

After the discovery of Chiron in 1977 (Kowal 1979) the space between the orbits of the outer planets has been rapidly filling with bodies that are thought to be either en route between the trans-Neptunian belt and the Jupiter family of comets, or evolving in the opposite direction, after perhaps a stay within the orbit of Jupiter (Duncan et al. 2004).

5.2. The scattered disk

Duncan and Levison (1997) showed that the picture of a trans-Neptunian belt of objects in low-eccentricity, low-inclination orbits is in fact oversimplified. Numerous objects can be efficiently scattered by Neptune on more elongated orbits, with aphelia still not reaching distances typical of the Oort cloud, and can remain in this "scattered disk" for billions of years, before being further scattered, or recaptured into smaller orbits, by Neptune.

5.3. Oort cloud formation/evolution, and the role of external perturbers

Revived interest for the dynamics of comets in the Oort cloud has concentrated on the modeling of external cloud perturbers, which are essential for the reconstruction of the formation and evolution of the cloud and for determining its population and total mass (Dones et al. 2004). Rickman et al. (2008) have re-evaluated the role of stellar perturbations vs. the Galactic tide and have shown that the two work in synergy, with the total effect being significantly larger that the sum of the two individual contributions.

5.4. Non gravitational forces modeling

The availability of abundant and good quality astrometric data on comets has allowed substantial improvements in the modelization of non gravitational forces (Yeomans et al. 2004). In particular, the consideration of discrete jets on rotating nuclei, coupled with modeling of the spin axis precession and of seasonal effects, allow substantial improvements in the orbital fits (Chesley and Yeomans 2005).

5.5. Meteor storm forecasting

Prompted by the return to perihelion of the Leonid parent and by work by Kondrat'eva et al. (1997), Asher (1999) and McNaught and Asher (1999) developed a model of dust trail emitted by the comet that has proven to be very effective for the prediction of meteor storms, and has thereafter come into widespread use.

References

Asher, D. J. 1999, MNRAS 307, 919
Chesley, S. R., Yeomans, D. K. 2005, in Dynamics of Populations of Planetary Systems, Proc. IAUC 197 (Z. Knežević and A. Milani eds.), Cambridge Univ. Press, Cambridge, 289
Chesley, S. R., Ostro, S. J., Vokrouhlický, D., Čapek, D., Giorgini, J. D., Nolan, M. C., Margot, J.-L., Hine, A. A., Benner, L. A. M., Chamberlin, A. B. 2003, Science 302, 1739
Dones, L., Weissman, P. R., Levison, H. F., Duncan, M. J. 2004, in Comets II (M. C. Festou, H. U. Keller, and H. A. Weaver eds.), Univ. Arizona Press, Tucson, 153
Duncan, M. J., Levison, H. F. 1997, Science 276, 1670
Duncan, M., Levison, H., Dones, L. 2004, in Comets II (M. C. Festou, H. U. Keller, and H. A. Weaver eds.), Univ. Arizona Press, Tucson, 193
Farinella, P., Vokrouhlický, D., Hartmann, W. K. 1998, Icarus 132, 378-387.
Gomes, R., Levison, H. F., Tsiganis, K., Morbidelli, A. 2005, Nature 435, 466
Gutzwiller, M. 1998, Rev. Mod. Phys. 70, 589
Guzzo, M., Morbidelli, A. 1996, CeMDA 66, 255
Ivezić, Ž., Tyson, J. A., Jurić, M., Kubica, J., Connolly, A., Pierfederici, F., Harris, A. W., Bowell, E., Null, N. 2007, in Near Earth Objects, our Celestial Neighbors: Opportunity and Risk, Proc. IAUS 236 (A. Milani, G. B. Valsecchi and D. Vokrouhlický eds.), Cambridge Univ. Press, Cambridge, 353
Jedicke, R., Magnier, E. A., Kaiser, N., Chambers, K. C. 2007, in Near Earth Objects, our Celestial Neighbors: Opportunity and Risk, Proc. IAUS 236 (A. Milani, G. B. Valsecchi and D. Vokrouhlický eds.), Cambridge Univ. Press, Cambridge, 341
Jewitt, D., Haghighipour, N. 2007, ARA&A 45, 261
Kondrat'eva, E. D., Murav'eva, I. N., Reznikov, E. D. 1997, Sol. Syst. Res. 31, 489
Kowal, C. T. 1979, in Asteroids (T. Gehrels ed.), Univ. Arizona Press, Tucson, 436
Larson, S. 2007, in Near Earth Objects, our Celestial Neighbors: Opportunity and Risk, Proc. IAUS 236 (A. Milani, G. B. Valsecchi and D. Vokrouhlický eds.), Cambridge Univ. Press, Cambridge, 323
Laskar, J. 1989, Nature 338, 237
Laskar, J. 2008, Icarus 196, 1
Laskar, J., Robutel, P. 1993, Nature 361, 608
Laskar, J., Joutel, F., Robutel, P. 1993, Nature 361, 615
Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. C. M., Levrard, B. 2004, A&A428, 261
LeVerrier, U. J. 1857, Annales de l'observatoire de Paris 3, 203
Lexell, A. J. 1778, Acta Academiae Scientiarum Imperialis Petropolitanae II, 12
McNaught, R. H., Asher, D. J. 1999, JIMO 27, 85
Merline, W. J., Weidenschilling, S. J., Durda, D. D., Margot, J. L., Pravec, P., Storrs, A. D. 2002, in Asteroids III (W. F. Bottke Jr., A. Cellino, P. Paolicchi, and R. P. Binzel eds.), Univ. Arizona Press, Tucson, 289
Milani, A., Chesley, S. R., Valsecchi, G. B. 1999, A&A346, L65
Milani, A., Chesley, S. R., Sansaturio, M. E., Tommei, G., Valsecchi, G. B. 2005, Icarus 173, 362
Milani, A., Valsecchi, G. B., Vokrouhlický, D. (eds.) 2007, Near Earth Objects, our Celestial Neighbors: Opportunity and Risk, Proc. IAUS 236, Cambridge Univ. Press, Cambridge
Morbidelli, A. 1997, Icarus 127, 1
Morbidelli, A., Levison, H. F., Tsiganis, K., Gomes, R. 2005, Nature 435, 462
Nesvorný, D., Ferraz-Mello, S., Holman, M., Morbidelli, A. 2002a, in Asteroids III (W. F. Bottke Jr., A. Cellino, P. Paolicchi, and R. P.

Binzel eds.), Univ. Arizona Press, Tucson, 379
Nesvorný, D., Bottke, W. F., Jr., Dones, L., Levison, H. F. 2002b, Nature 417, 720
Nesvorný, D., Vokrouhlický, D. 2006, AJ 132, 1950
Noll, K. S. 2006, in Asteroids, Comets, Meteors, Proc. IAUS 229 (D. Lazzaro, S. Ferraz-Mello, J. A. Fernández eds.), Cambridge Univ. Press, Cambridge, 301
Noll, K. S., Grundy, W. M., Chiang, E. I., Margot, J.-L., Kern, S. D. 2008, in The Solar System Beyond Neptune (M. A. Barucci, H. Boehnhardt, D. P. Cruikshank, and A. Morbidelli eds.), Univ. Arizona Press, Tucson, 345
Peale, S. J. 1999, ARA&A 37, 533
Peale, S. J., Cassen, P., Reynolds, R. T. 1979, Science 203, 892
Rickman, H., Fouchard, M., Froeschlé, C., Valsecchi, G. B. 2008, CeMDA, in press
Rubincam, D. P. 1995, JGR 100, 1585
Rubincam, D. P. 2000, Icarus 148, 2
Tsiganis, K., Gomes, R., Morbidelli, A., Levison, H. F. 2005, Nature 435, 459
Valsecchi, G. B., Milani, A., Gronchi, G. F., Chesley, S. R. 2003, A&A408, 1179
Vokrouhlický, D., Chesley, S. R., Matson, R. D. 2008, AJ 135, 2336
Yeomans, D. K., Chodas, P. W., Sitarski, G., Szutowicz, S., Królikowska, M. 2004, in Comets II (M. C. Festou, H. U. Keller, and H. A. Weaver eds.), Univ. Arizona Press, Tucson, 137