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COMMISSION 7 — CELESTIAL MECHANICS AND DYNAMICAL ASTRONOMY

MÉCANIQUE CÉLESTE ET ASTRONOMIE DYNAMIQUE

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TRIENNIAL REPORT 2009-2012

1. Introduction

At the time this report was written, Commission 7 according to the IAU database had 304 registered members. The activities of Commission 7 in the past triennium closely followed the plan outlined at the business meeting of the Commission held on August 5, 2009 in Rio de Janeiro (Transactions IAU, Volume XXVIIB, 119-120). They can be summarized as follows:

- Preparation of the Terms of Reference of Commission 7. The document contains the scientific rationale and lists a number of the most important objectives of Commission 7, thus justifying its continued existence and activity. Several colleagues contributed to the preparation of this important document, its final form being done by Z. Knežević and A. Morbidelli.
- A complete remake and transfer of the Commission 7 web site to a new address: http://staff.on.br/iaucom7/. The web page has a new design, authored by F. Roig; it contains a number of new features and useful information, and is regularly updated.
- Taking advantage of the possibility offered by the current Statutes and By-Laws of the IAU, the initiative for the co-affiliation of Commission 7 with Division III while keeping its original affiliation with Division I, has been proposed by A. Morbidelli, who also prepared the rationale for the proposal. Commission 7 had a vote on the proposal which showed that a vast majority of the Commission members favor the co-affiliation. The initiative has also been officially supported by the Division I Organizing Committee. We are expecting only the consent by Division III to submit the proposal to the IAU.
- An initiative for the Asteroid Dynamic Site (AstDyS) to become a permanent IAU service has been proposed by A. Milani, Z. Knežević and M. E. Sansaturio. The proposal is in response to a wider initiative of Division I for establishment of permanent services under the auspices of the IAU. The motion is currently awaiting the completion of the ongoing restructuring of the IAU Divisions to be submitted to the relevant IAU bodies.
- Commission 7 officers actively participated in the activities of Division I Organizing Committee. A. Morbidelli served as a representative of Commission 7 in the Subcommittee for restructuring, created by the Division I.

• A significant effort has been put in an attempt to win organization of an IAU symposium in 2012. A. Milani, S. Mikkola and Z. Knežević prepared the two-stage proposal. Unfortunately, the proposal was not accepted by the IAU, thus our field remains without an IAU Symposium for an extended period of time.

• The President, vice-president and secretary of the Commission took care of various administrative and current businesses which were brought to their attention by members of the commission, officers of Division I and of the IAU.

• Commission 7 was involved with the interdivision Working group on Natural Planetary Satellites , which made progress in the theoretical modeling of motions of the main satellites of Jupiter and Saturn by including tidal effects and introducing constraints on the internal structures. The detailed report is included in the IAU Transactions.

• Finally, an important task of the Commission 7 was the preparation of this report.

2. Developments within the past triennium

2.1. *Chaos in galaxies*

E. Athanassoula, M. Romero-Gómez & E. Vasiliev

A number of papers considered various methods of determination of orbital class and degree of chaos. Most of them are based on the calculation of the Lyapunov characteristic exponents (LCE) and their derivatives. Skokos (2010) presents a comprehensive review of various applications of LCE. Manos *et al.* (2011) applied the Generalized ALignment Index (GALI) to study dynamical properties of orbits in the vicinity of a periodic orbit. Maffione *et al.* (2011a) focused on the MEGNO indicator (Mean Exponential Growth of Nearby Orbits) and applied it to study orbits in a triaxial galactic potential, while Maffione *et al.* (2011b) presented a detailed comparison of several chaos indicators. They find that FLI/RLI (Fast and Relative Lyapunov Indicator) are most suitable for analyzing global dynamics of the system, while MEGNO and GALI perform better at the level of individual orbits. Among the methods not related to LCE, 4D surfaces of section were used by Katsanikas *et al.* (2011) in application to multiply-periodic orbits. Bountis *et al.* (2011) used probability distributions of sum of coordinates to distinguish weakly chaotic from strongly chaotic orbits in a barred galaxy potential.

The role of chaotic orbits in the evolution and dynamics of spheroids was considered in several papers. Muzzio *et al.* (2009) find that triaxial cuspy models can have a large fraction of chaotic orbits and still be reasonably stable over many dynamical times. Valluri *et al.* (2009) studied the effect of baryonic contraction on the orbital structure of triaxial DM halos and the change of shape induced by the evolution of chaotic orbits, while Valluri *et al.* (2011) applied also frequency analysis to study the Galactic halo. Deibel *et al.* (2011) surveyed the orbital structure of triaxial cuspy galaxies with slow figure rotation. Vandervoort (2011) explores chaotic behavior in a model of homologous oscillations of an axisymmetric galaxy (whose size but not shape changes in time).

Work was also done to establish the influence of chaos, and in particular of 'sticky' or 'confined' orbits, on galactic structures. Manifolds, linked to the unstable periodic orbits around the L1 (L2), are proposed to explain both the spirals and the rings in barred galaxies. Athanassoula *et al.* (2009a) find that the bar strength determines whether the morphology is that of a ring or a spiral. In the former case the R1, R2 and R1R2 morphologies are explained, while in the latter, a clear link between the bar strength and the spiral pitch angle is found (Athanassoula *et al.* 2009b) and confirmed by Martínez-García (2011). Finally, Athanassoula *et al.* (2010) present comparisons to observations,

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while Romero-Gómez *et al.* (2011) apply this theory to our Galaxy. A different approach, still based on manifolds, but relying on the apsidal sections (pericenters and apocentres) of the manifolds was elaborated by Tsoutsis *et al.* (2009), Contopoulos & Harsoula (2010), Efthymiopoulos (2010) and Harsoula *et al.* (2011). This second approach necessitates a bar that either does not evolve, or evolves at a much slower rate than what is necessary for the first approach, i.e. no or little secular evolution. Patsis *et al.* (2009, 2010) analysed the orbital structure in NGC 3359 and 1300, using response models and making morphological comparisons. Harsoula & Kalapotharakos (2009) used frequency analysis to distinguish between regular and chaotic orbits in an N-body system. Manos & Athanassoula (2011) find a strong correlation between the bar strength and the fraction of orbits in the bar region that is chaotic. Finally, Shevchenko (2011) gave estimates of the Lyapunov and diffusion timescales in the solar neighborhood.

References

Athanassoula, E., Romero-Gómez, M., & Masdemont, J. J. 2009, *MNRAS*, 394, 67
Athanassoula, E., Romero-Gómez, M., Bosma, A., & Masdemont, J. J. 2009, *MNRAS*, 400, 1706
Athanassoula, E., Romero-Gómez, M., Bosma, A., & Masdemont, J. J. 2010, *MNRAS*, 407, 1433
Bountis, T., Manos, T., & Antonopoulos, Ch., 2011, arXiv:1108.5059
Contopoulos, G. & Harsoula, M., 2010, *CeMDA*, 107, 77
Deibel, A., Valluri, M., & Merritt, D., 2011, *ApJ*, 728, 128
Efthymiopoulos, C., 2010, *The European Physical Journal Special Topics*, 186, 91
Harsoula, M. & Kalapotharakos, C., 2009, *MNRAS*, 394, 1605
Harsoula, M., Kalapotharakos, C., & Contopoulos, G., 2011, *MNRAS*, 411, 1111
Katsanikas, M., Patsis, P., & Pinotsis, A., 2011, arXiv:1103.3981
Maffione, N., Giordano, C., & Cincotta, P., 2011a, arXiv:1108.5481
Maffione, N., Darriba, L., Cincotta, P., & Giordano, C., 2011b, arXiv:1108.2196
Manos, T. & Athanassoula, E., 2011, *MNRAS*, 415, 629
Manos, T., Skokos, Ch., & Antonopoulos, Ch., 2011, arXiv:1103.0700
Muzzio, J., Navone, H., & Zorzi, A., 2009, *CeMDA*, 105, 379
Patsis, P. A., Kaufmann, D. E., Gottersman, S. T., & Boonyasait, V. 2009, *MNRAS*, 394, 142
Patsis, P. A., Kalapotharakos, C., & Grosbol, P. 2010, *MNRAS*, 408, 22
Romero-Gómez, M., Athanassoula, E., Antoja, T., & Figueras, F., 2011, arXiv:1108.0660
Shevchenko, I. I., 2011, *ApJ*, 733, 39
Skokos, Ch., 2010, *Lect. Notes Phys.* 790, 63
Tsoutsis, P., Kalapotharakos, C., Efthymiopoulos, C., & Contopoulos, G. 2009, *A& A*, 495, 743
Valluri, M., Debattista, V., Quinn, T., & Moore, B., 2010, *MNRAS*, 403, 525
Valluri, M., Debattista, V., Quinn, T., Roskar, R., & Wadsley, J., 2011, arXiv:1109.3193
Vandervoort, P., 2011, *MNRAS*, 411, 37

2.2. *New results on the chaotic behavior of the Solar System*

J. Laskar

The discovery of the chaotic behavior of the planetary orbits in the Solar System (Laskar 1989) was obtained using numerical integration of averaged equations of motion. This chaotic behavior of the Solar System manifests itself by an exponential divergence of nearby trajectories, the distance between two orbital solutions being multiplied by ten every ten million years which limits the validity of the solutions to less than 100 Myr. A numerical integration of the Solar System motion over 5 Gyr can only be considered as a random sample of its possible evolution and statistical studies are required.

The first study over several Gyr made use of the numerical integration of the averaged equations (Laskar 1994) revealing the possibility for the eccentricity of Mercury to reach

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very high values, beyond 0.7, allowing for collisions with Venus in less than 5 Gyr. The drawback of this early study is that the averaged equations are no longer justified in the vicinity of a collision. This result has been unchallenged for 15 years.

Large progress has been achieved recently. A first statistical study using the secular equations for 1000 solutions over 5 Gyr has shown that the probability of a large increase of the eccentricity of Mercury over 5 Gyr is about 1% for the full model, but raises to more than 50% when general relativity is not taken into account in the model, which was confirmed by a test over 10 solutions with the non averaged Newtonian equations (Laskar 2008). At the same time, Batyugin & Laughlin (2008) have reproduced the experiment of Laskar (1994) with a Newtonian model and have confirmed that high values of the eccentricity of Mercury can occur, leading to possible collision with Venus. The large increase of the eccentricity of Mercury is obtained through a secular resonance between the perihelion motion of Mercury and the perihelion motion of Jupiter (Laskar 2008; Batyugin & Laughlin 2008). When general relativity (GR) is removed, the perihelion speed of Mercury gets closer to the one of Jupiter, which explains why the non relativistic system is much more unstable than the full model (Laskar 2008).

Finally, a full scale statistical simulation over 5 Gyr, with the full Solar System with GR and non-averaged equations, has been performed, gathering 2501 solutions with very close initial conditions (Laskar & Gastineau 2009).This study confirmed that the probability for a destabilization of the system, with a very large increase of the eccentricity of Mercury is about 1%. It was also shown that once the eccentricity of Mercury raise to very high level, actual collisions of Mercury with Venus or with the Sun are the most probable outcome. In some cases, the large increase of Mercury's eccentricity was followed by a total destabilization of the inner Solar System, with possible collision of any two planets of the inner Solar System (Mercury, Venus, Earth, Mars) in less than 5 Gyr. A joined test with pure Newtonian equations over 200 orbits shows that in this case the probability for high increase of Mercury leading to possible collision increases to about 60%.

The search for the best solution for the Earth's orbit over millions of years is motivated by the possibility to calibrate the recent geological timescales by correlation of the geological stratigraphic data to the computed variation of the insolation on Earth. Indeed, in the latest geological timescale adopted by the International Union of Geological Sciences (IUGS), the Neogene period (0-23.03 Ma) is now calibrated astronomically (Lourens *et al.* 2004). Since then, there has been a continuous effort to extend this astronomical calibration to the entire Cenozoic era, over about 65 Ma. The latest improvement in the long-term astronomical solution has been obtained through a complete revision of the numerical algorithm and the construction of the high-precision short-term planetary ephemerides INPOP (Fienga *et al.* 2008; 2009; 2011) that were extended over 1 Myr as a reference for the long-term solutions. Despite this effort, this new solution is valid over 50 Myr only (Laskar *et al.* 2011a).

The reasons of these difficulties in the construction of a long-term solution for the planetary orbits are now identified and are due to the highly chaotic behavior of Ceres and Vesta resulting from close encounters (Laskar *et al.* 2011b). As a result, their positions will be totally lost in less than 400 kyr. Despite their small mass, Ceres and Vesta perturb the planetary orbits. Due to these interactions, the eccentricity of the Earth becomes unpredictable after 60 Myr, somewhat less than the duration of the Cenozoic era.

As the NASA/Dawn spacecraft will be orbiting Vesta for several months before continuing its route towards Ceres, one can expect that the precision on the positions of these minor bodies will be improved. But this will be of no use for paleoclimate studies. Indeed, even if the initial error in these positions is reduced to 1.5 mm, their positions will still be in total error after less than 500 kyr, and there will be no significant change in the time of validity of the orbital solution of the Earth. This limit of 60 Myr thus appears as an absolute limit for a precise prediction of the Earth's eccentricity, that will not be beaten easily in the future.

References

Batygin, K. & Laughlin, G. 2008, *ApJ*, 683, 1207
Fienga, A., Manche, H., Laskar, J., & Gastineau, M. 2008, *A& A*, 477, 315
Fienga, A., Laskar, J., Morley, T., *et al.* 2009, *A& A*, 507, 1675
Fienga, A., Laskar, J., Kuchynka, P., *et al.* 2011, *CeMDA*, 111, 363
Laskar, J. 1989, *Nature*, 338, 237
Laskar, J. 1994, *A& A*, 287, L9
Laskar, J. 2008, *Icarus*, 196, 1
Laskar, J. & Gastineau, M. 2009, *Nature*, 459, 817
Laskar, J., Robutel, P., Joutel, F., *et al.* 2004, *A& A*, 428, 261
Laskar, J., Fienga, A., Gastineau, M., & Manche, H. 2011a, *A& A*, 532, 89
Laskar, J., Gastineau, M., Delisle, J., Farrés, A., & Fienga, A. 2011b, *A& A*, 532, L4
Lourens, L., Hilgen, F., Laskar, J., Shackleton, N., & Wilson, D. 2004, in: F. Gradstein, J. Ogg, & A. Smith (eds.) ed. F. Gradstein, J. Ogg, & A. Smith *A Geological Timescale 2004*, 409–440

2.3. *Dynamical mechanisms for the origin of retrograde extrasolar planets*

D. Nesvorny & R. Malhotra

Around 1% of solar-type stars host Jupiter-mass planets with the semimajor axis a less than 0.1 AU. It is thought that these planets, the so-called *hot Jupiters*, did not form in situ because the region within 0.1 AU was too hot and rarefied for a Jupiter-mass planet to form. Instead, the hot Jupiters probably formed several AU from their host stars, and later migrated inward.

Planets are thought to have radially migrated due to their interaction with the protoplanetary gas disk from which they formed. Yet, several orbital properties of hot Jupiters suggest that at least some of the observed hot Jupiters, if not most, arrived to their current orbits *after* the gas disk dispersal. For example, many hot Jupiters with $0.05 < a < 0.1$ AU have unexpectedly large orbital eccentricities ($e > 0.2$), whereas the the gas disk should efficiently damp e and produce nearly circular orbits, $e \approx 0$.

To date, the Rossiter-McLaughlin effect has been measured for 37 planets (mostly hot-Jupiters; Moutou *et al.* 2011). In about half of these cases the planet orbit normal is probably aligned with the stellar spin vector ($|\lambda| < 30°$, where λ is the projected spin-orbit misalignment angle), however, in 8 cases ($\sim 20\%$) the planets are inferred to have retrograde orbits. The origin of retrograde hot Jupiters is an intriguing problem.

To produce large values of $|\lambda|$, it is either necessary to tilt the spin axis of the star so that it ends up being misaligned with the original protoplanetary disk in which the planets formed, or to tilt the planetary orbit. A tilt of the star's axis can be produced by a number of effects including the late non-isotropic (Bondi-Hoyle) accretion on the star (Throop & Bally 2008; see also Thies *et al.* 2011), and interaction between the stellar magnetic field and protoplanetary disk (Lai *et al.* 2011).

An orbital tilt can be produced by: (i) Planetary scattering followed by Kozai migration (Nagasawa *et al.* 2008); (ii) Kozai migration due to a distant perturber in an inclined orbit (Fabrycky & Tremaine 2007, Wu *et al.* 2007, Naoz *et al.* 2011, Correia *et al.* 2011, Katz *et al.* 2011); and (iii) Secular migration in well-spaced, eccentric, and inclined planetary systems (Wu & Lithwick 2011).

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The spin- and orbit-tilt theories have different implications. For example, the spin-tilt theory implies that co-planar planetary systems with large values of $|\lambda|$ should be relatively common, while the mutual inclinations of planets should be generally high according to the orbit-tilt theory. Interestingly, at least some planetary systems have large orbital inclinations (McArthur *et al.* 2010).

In addition, the observed large eccentricities of exoplanets can be best explained if the original, closely-packed planetary systems underwent a dynamical instability followed by planet scattering (Weidenschilling & Marzari 1996, Rasio & Ford 1996), and tidal circularization of close-in planets (Jackson *et al.* 2008). As planet scattering naturally leads to large orbital inclinations as well, the orbital tilt theories are therefore a logical extension of the planet scattering model.

Beaugé & Nesvorný (2011) performed numerical simulations of planet scattering followed by tidal circularization and migration of planets that evolved into highly eccentric orbits. They found that orbits typically acquire high eccentricities and high inclinations due to close encounters and subsequent slow secular interactions, rather than due to the sole effect of the Kozai resonance. Their final results provide a good match to the period and eccentricity distribution of hot Jupiters.

The inclination distribution of hot Jupiters appears to be sensitive to the number of planets in the initial systems, N. While very few hot Jupiters form in retrograde orbits for $N = 3$, the case with $N = 4$ shows a larger proportion ($\sim 10\%$), and a wider spread in inclination values. As the latter result better agrees with observations, this may suggest that the planetary systems with observed hot Jupiters were originally rich in the number of planets, some of which were ejected. In a broad perspective, this hints on an unexpected link between the hot Jupiters and recently discovered free floating planets (Sumi *et al.* 2011).

References

Beauge, C. & Nesvorny, D. 2011, arXiv:1110.4392
Correia, A. C. M., Laskar, J., Farago, F., & Boué, G. 2011, *CeMDA*, 111, 105
Fabrycky, D. & Tremaine, S. 2007, *ApJ*, 669, 1298
Jackson, B., Greenberg, R., & Barnes, R. 2008, *ApJ*, 678, 1396
Katz, B., Dong, S., & Malhotra, R. 2011, arXiv:1106.3340
Lai, D., Foucart, F., & Lin, D. N. C. 2011, *MNRAS*, 412, 2790
McArthur, B. E., Benedict, G. F., Barnes, R., *et al.* 2010, *ApJ*, 715, 1203
Moutou, C., Díaz, R. F., Udry, S., *et al.* 2011, *A& A*, 533, A113
Nagasawa, M., Ida, S., & Bessho, T. 2008, *ApJ*, 678, 498
Naoz, S., Farr, W. M., Lithwick, Y., Rasio, F. A., & Teyssandier, J. 2011, *Nature*, 473, 187
Rasio, F. A. & Ford, E. B. 1996, *Science*, 274, 954
Sumi, T., Kamiya, K., Bennett, D. P., *et al.* 2011, *Nature*, 473, 349
Thies, I., Kroupa, P., Goodwin, S. P., Stamatellos, D., & Whitworth, A. P. 2011, *MNRAS*, 417, 1817
Throop, H. B. & Bally, J. 2008, *AJ*, 135, 2380
Weidenschilling, S. J. & Marzari, F. 1996, *Nature*, 384, 619
Wu, Y. & Lithwick, Y. 2011, *ApJ*, 735, 109
Wu, Y., Murray, N. W., & Ramsahai, J. M. 2007, *ApJ*, 670, 820

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