CELMEC VI
1-6 September 2013
Book of Abstracts: Talks and Posters

1 Talks

Albouy, A., Paris Observatory/CNRS (France), Two quadratic conserved quantities (invited talk)

We will argue against a judgement by Jacobi, cited in Arnold's book on classical mechanics:

"The main difficulty in integrating a given differential equation lies in introducing convenient variables, which there is no rule for finding."

In particular, we will show that one can integrate the two-fixed center problem with simple geometrical and dynamical ideas, which includes discovering the mysterious quadratic conserved quantity without any specific computation, and understand how this method extends or does not extend to other fixed attractors. We will use the projective invariance of the Kepler problem discovered by Halphen in 1877. Then we will recall the obvious geometrical rule for finding separating variables. We will continue with higher dimensional considerations, in particular, by giving our last news with Lundmark about his discovery in 1999: "two quadratic conserved quantities implies integrability".

Alessi, E.M., IFAC-CNR (Italy), The geometry of impacts on a synchronous planetary satellite

We consider a satellite in a circular orbit about a planet, that is in turn in a circular orbit about the Sun; we further assume that the plane of the planetocentric orbit of the satellite is the same as that of the heliocentric orbit of the planet. The pair planet-satellite is encountered by a population of small bodies on planet-crossing, inclined orbits. With this setup, and using the extension of Opikś theory by Valsecchi, Milani, Gronchi and Chesley (2003), we analytically compute the velocity and the elongation from the apex of the bodies impacting the satellite, as simple functions of the heliocentric orbital elements of the impactor and of the longitude of the satellite at impact. The relationships so derived are of interest for satellites in synchronous rotation, since they can shed light on the degree of apex-antapex cratering asymmetry that some of these satellites show.

Batkhin, A., Keldysh Institute of Applied Mathematics of RAS (Russia), Families of symmetric periodic solutions of a generalized Hillś problem

We consider a generalization of the well-known plain Hill's problem and investigate its families of symmetric periodic solutions of the second kind after Poincaré. All these families are obtained from its generating solutions in the form of finite sequence of arc-solutions, which begin and finish at the origin the singular point of the equations of motion. The generating sequence makes it possible to predict such properties of corresponding family as type of symmetry, global multiplicity of the family's orbits and approximation of initial conditions. Classification of all known and recently found new families was done in terms of its generating sequences. It was shown that all these families form a kind of global network if we consider the Hill's problem with Newtonian potential of attraction and repulsion as well. More then 20 new families of periodic solutions contain orbits that make definite number of revolutions around libration points L1 and/or L2 a nd around Earth.

Baù, G., Università di Pisa (Italy), Efficient orbit computation using new time-elements

We derive new time-elements for the two-body problem by exploiting a transformation from the physical time to a fictitious time that resembles the true anomaly. This ¨generalized Sundman transformation¨(1) has been recently (3) employed to enhance the performance of a method due to Pelàez et al. (2) which is based on seven elements linked to the variables of the Burdet-Ferràndiz regularization. The resulting generalized orbital elements (3) are here used along with the proposed time-elements to propagate the perturbed two-body motion. Numerical tests carried out by considering the elliptic motion around the Earth with different eccentricity regimes and perturbation types show the notable improvement in terms of accuracy and error accumulation in long-term propagations of the new formulation with respect to the methods presented in references (2) and (3). Moreover, the method is better than two efficient sets of elements developed by Stiefel & Scheifele and Sperling & Burdet.

(1) Sharaf, M. A., Awad, M. E., and Najmuldeen, S. A. A. ¨Motion of artificial satellites in the set of Eulerian redundant parameters (III)¨, Earth, Moon, and Planets, Vol.56, No. 2, 1992, pp. 141-164

(2) Peláez, J., Hedo, J. M., and de Andres, P. R., ¨A special perturbation method in orbital dynamics¨, Celestial Mechanics and Dynamical Astronomy, Vol. 97, No. 2, 2007, pp. 131-150

(3) Baú, G., Bombardelli, C., and Peláez, J., ¨A new set of integrals of motion to propagate the perturbed two-body problem¨, Celestial Mechanics and Dynamical Astronomy (doi:10.1007/s10569-013-9475-x)

Bernardi, F., Cibin, L., SpaceDyS and CGS (Italy), Fly Eye Telescope and Advanced Orbit Determination Asset: a Product Synergy between Hardware and Software for the Space Situational Awareness Program

Joint work with M. Chiarini, A. Milani, L. Dimare, G. Valsecchi, A. Rossi, R. Ragazzoni, P. Salinari. Compagnia Generale per lo Spazio (CGS SpA), formerly Carlo Gavazzi Space, has consolidated an Italian Consortium, comprising the Mathematics Department of Pisa @ Ys University (DM), Space Dynamics Services (SpaceDyS), the Institute for Applied Physics (CNR-IFAC) and the Italian National Institute for Astrophysics (INAF), which has acquired a recognised experience on Space Situational Awareness (SSA) problematic. The Italian Team has demonstrated the feasibility of and optical observation Network based on a core optical element, the Fly-Eye Telescope, allowing to monitor and catalogue objects belonging to all orbital belts, i.e. GEO, MEO and High LEO, and characterised by dimensions that, depending on the observed belt, are of particular interest for catastrophic collision avoidance (e.g. in high LEO 8cm diameter objects can be monitored down to 1000 km of perigee altitude). This capability is based on the tight synergy between three fundamental elements: an innovative optical architecture based on the Fly-Eye technology, (allowing a huge field of view of about 45 square degrees with a resolution better than 1.5 arcseconds joined to a 1m equivalent aperture and provided with fast motion performances), a set of new image processing techniques, (allowing to extract faint object trails in conditions prohibitive for traditional methods), and a system of advanced orbit determination methods. These advanced orbit determination methods are either based on the "admissible region" (AR) technique or by the "first integrals" (FI) technique of the Kepler problem, developed by our team. Both methods require less data than the classical Gauss approach, and therefore less sensor resources are needed. Moreover, the computational load is nlog(n) for AR and n2 for FI, while the classical approach is n3. In particular, the FI method is necessary when dealing with fast evolving space debris such as LEOs, for which subsequent tracklets are taken even after some orbit revolutions. All the above described elements constitute the fundamental components for the implementation of a National Demonstrator Asset allowing to respond to Space Surveillance and Tracking (SST) needs in collaboration with existing Radar Assets, with full operational capability. The aim of this work is to illustrate the basic concepts allowing the implementation of the SST National Asset based on the advanced HW and SW solutions proposed by our Team, and to analyze the capabilities offered by the proposed Demonstrator System.

Biasco, L., Università di Roma tre (Italy), Analytic estimates and topological properties of the weak stability boundary

The weak stability boundary (WSB) is the transition region of the phase space where the change from gravitational escape to ballistic capture occurs. Studies on such complicate region of chaotic motion aim to investigate its unique, fuel saving properties to enlarge the frontiers of low energy transfers. As such "fuzzy stability" region is characterized by highly sensitive motion, any analysis of it has been carried on almost exclusively by numerical methods On the contrary this paper provides, of the planar circular restricted 3 body problem (PCR3BP), 1) an analytic definition of the WSB which is coherent with the known algorithmic definitions; 2) a precise description of the topology of the WSB; 3) analytic estimates on the "stable region" (nearby the smaller primary), whose boundary is, by definition, the WSB. Joint work with Marta Ceccaroni and James Biggs.

Boué, G., University of Chicago (US), Evolution of compact multiplanet systems with a wide companion

Several tightly packed exoplanet systems surrounded by a wide companion have been detected. I will describe the secular evolution of this class of system using a geometrical approach developed for the lunar problem (Boue & Laskar, 2006;

Boue & Laskar, 2009). More specifically, I will show how this geometric method depicts the dynamical evolution of the mutual inclinations in those multiple systems. Joint work with Daniel Fabrycky

Campagnola, S., ISAS/JAXA (Japan), Resonant hopping and space mission design (invited talk)

Resonant hopping is a mechanism by which a spacecraft has repeated flybys with a secondary body (moon or planet), connected by resonant orbits (i.e. with period commensurable to the period of the secondary around the primary). With propulsive manoeuvres in between flybys, resonant hopping is a powerful technique in space mission design. This talk summarizes our recent developments in the understanding and design of DV-resonant hopping, and their implementation to proposed, approved and flying missions from NASA , ESA, and JAXA.

Carruba, V., UNESP (Brasil), A multi-domain approach to asteroid family identification

It has been shown that large families are not limited to what found by hierarchical clustering methods (HCM) in the domain of proper elements (a,e,sin(i)), that seems to be biased to find compact, relatively young clusters, but that there exists an extended population of objects with similar taxonomy and geometric albedo, that can extend to much larger regions in proper elements and frequencies domains: the family "halo". Numerical simulations can be used to provide estimates of the age of the family halo, that can then be compared with ages of the family obtained with other methods. Determining a good estimate of the possible orbital extension of a family halo is therefore quite important, if one is interested in determining its age and, possibly, the original ejection velocity field. Previous works have identified families halos by an analysis in proper elements domains, or by using Sloan Digital Sky Survey-Moving Object Catalog data, fourth release (SDSS-MOC4) multi-band photometry to infer the asteroid taxonomy, or by a combination of the two methods. The limited number of asteroids for which geometric albedo was known until recently discouraged in the past the extensive use of this additional parameter, which is however of great importance in identifying an asteroid taxonomy. The new availability of geometric albedo data from the Wide-field Infrared Survey Explorer (WISE) mission for about 100,000 asteroids significantly increased the sample of objects for which such information, with some errors, is now known. In this work we proposed a new method to identify families halos in a multi-domain space composed by proper elements, SDSS-MOC4 (a*,i-z) colors, and WISE geometric albedo for the whole main belt (and the Hungaria and Cybele orbital regions). Assuming that most families were created by the breakup of an undifferentiated parent body, they are expected to be homogeneous in colors and albedo. The new method is quite effective in determining objects belonging to a family halo, with low percentages of likely interlopers, and results that are quite consistent in term of taxonomy and geometric albedo of the halo members.

Ceccaroni, M., Università di Roma 'Tor Vergata' (Italy), Double averaging method for frozen orbits around an inhomogeneous body

Orbital motion about irregular bodies is highly nonlinear due to inhomogeneities in the gravitational field. Classical theories of motion close to spheroidal bodies cannot be applied as, for inhomogeneous bodies, some spherical harmonics coefficients and the asteroid's fast rotation rate may dominate the dynamics. An analytical method for double averaging the motion of a spacecraft around a small irregular body (without expanding in series of the eccentricity) is presented, for the so called fast rotating case, which generalises previous results to second order, arbitrary degree, gravitational fields by means of Lie transformations. Applications of this algorithm include a method for determining initial conditions for frozen orbits around any irregular body by prescribing the desired inclination and eccentricity of the orbit. Frozen orbits are orbits with no secular perturbations in the inclination, argument of pericentre, and eccentricity. The method here described essentially reduces the problem of computing frozen orbits to a problem of solving a 2-D algebraic equation. Results are shown for the Jupiter Trojan 624-Hektor.

Chenciner, A, IMCCE, Paris (France), Angular momentum in higher dimensions and Horn's problem (invited talk)

Rigid motions of n point masses submitted to newtonian attraction necessarily take place in an euclidean space E of even dimension 2p. The initial (central) configuration being given, they are determined by a complex structure J on E compatible with the euclidean structure. The study of the angular momentum of such motions leads to the following purely algebraic question : Let S be a symmetric non negative matrix of size 2p (the inertia matrix of the initial configuration). What can be said of the mapping F which, to each J, associates the ordered spectrum of the J-hermitian matrix ,$S + J^{-1}SJ$, considered as a complex matrix ? On the other hand, Horn's problem asks for the possible spectra of matrices C=A+B, where A and B are hermitian (or real symmetric) with given spectra. Introducing two Hornś problems, in dimension p and in dimension 2p, one proves that the image of F is a convex polytope which can be described.

Cherubini, A.M., Università del Salento (Italy), A dynamical systems approach to detect early-warnings of transition to desertification in fragile eco-systems including habitable exoplanets

The identification of reliable early-warning signals of critical transitions is crucial for the safeguard of fragile ecosystems on Planet Earth, such as arid or semi-arid ones, strongly exposed to desertification risks. Moreover advancements in this area could be useful tools in the research for habitability in extrasolar planets. Previous studies suggested that some indicators of an approaching transition to desertification could be related to the evolution of vegetation patchiness. In this work we analyzed some ecological models for semi-arid ecosystems based on stochastic cellular automata (CA) which depends on a number of relevant parameters describing, beside soil and vegetation properties, external stresses. Recent studies mainly focus on the analysis of the spatial fluctuations of the vegetation patterns and indicate a significant deviation from power laws in vegetation patch size distributions as a reliable signal of approaching desertification. We have investigated the time fluctuations properties of the quantities associated with the steady states of two CA models. We found other possible and earlier signals related to percolation thresholds and to the time fluctuations distribution of the biggest cluster size. This results can be seen in a more general framework. A study of the dynamical system associated with the CA states was also performed (joint work with R. Corrado and C. Pennetta).

Chierchia, L., Università di Roma 3, (Italy), A theorem on (all) the spin-orbit resonances of the Solar system (invited talk)

In the mathematical framework of a simple, restricted, slightly dissipative spin-orbit model, we prove the existence of periodic orbits for parameter values corresponding to all the (24) satellites of the Solar system observed in an apparent spin-orbit resonance.

Colombo, C., Politecnico di Milano (Italy), Spacecraft proximity operation and control for asteroid rotation and orbit manipulation

This talk presents an analysis of the dynamics, navigation and control of a spacecraft in the proximity of a rotating asteroid, while the spacecraft deflects the asteroid's trajectory through laser ablation. During the deflection, the proximity motion of the spacecraft is coupled with the orbital and attitude motion of the asteroid. The combination of the deflection acceleration, solar radiation pressure, gravity field and plume impingement will force the spacecraft out of its motion in the proximity of the asteroid. In turn, a variation of the proximity motion of the spacecraft produces a change in the modulus and direction of the deflection action which modifies the attitude and orbital motion of the asteroid. The optimal distance of the spacecraft from the body will be computed, by taking into account the effect of contamination, which has an impact on the required thrusting time for the laser system. An on-board state estimation and control algorithm is then presented that simultaneously provides an optimal proximity control and an estimation of the asteroid's kinematics (joint work with Massimo Vetrisano, Massimiliano Vasile).

Conway, B., University of Illinois (USA), How Evolutionary and Heuristic Methods are Greatly Improving Spacecraft Trajectory Optimization (invited talk)

Spacecraft trajectory optimization has a very interesting history. Much work on both the impulsive and continuous-thrust cases was accomplished in the 1960's and 1970's, using the calculus of variations, and this work, including the well-known primer vector theory is of course still useful. However there are many modern problems, e.g problems with more than two bodies (incl. invariant manifold transfers), to which it does not apply. There are also many (e.g. very-low-thrust electric propulsion) trajectories where it does apply but yields numerical optimization problems that are very sensitive to initial conditions and may have other pathologies, such as convergence to only locally-minimizing solutions. Recent evolutionary optimization methods, such as Genetic Algorithms or Differential Evolution and heuristic methods such as the Particle Swarm, have in the last decade been applied to a wide variety of trajectory optimization problems with great success. These methods require no analytical necessary conditions for optimality (although there are circumstances where there is benefit to including the NC), are exceptionally simple to program, and locate global minima more reliably than conventional methods. Some of the evolutionary and heuristic methods will be described and their application to a variety of problems demonstrated, including optimal low-thrust transfer and rendezvous, optimal low-thrust + multiple flyby interplanetary missions, and optimal manned missions to near-Earth asteroids with constrained duration.

Deleflie, F., IMCCE, Paris (France), Long term stability of MEO and GTO-like orbits in the Earth environment

F. Deleflie, J. Daquin, M. Fouchard, A. Rossi, E. M. Alessi A. Vienne, N. Delsate, D. Hautesserres We detect the structure of the web of resonances in the MEO and GTO regions, in a model accounting for the non spherical shape of the Earth, the luni–solar perturbations and the solar radiation pressure. In particular, we study to what extent the change of initial parameters of storage orbits (namely and mainly the semi–major axis), can affect the long term stability of these orbits over very long time scales (typically, one century). The study is based on the numerical integration of the osculating equations of motion as well as on the numerical integration of averaged equations of motion (a semi-analytic method, suitable for all dynamical configurations), in a model that has been approved to be the reference one for the French Space Operations Act (through the dedicated software SATlight and STELA). Space debris mitigation is one objective of this law, in line with Inter-Agency Space Debris Coordination Committee recommendations, through removal of non-operational objects from populated regions. New functionalities have been implemented into the s/w, and in particular the computation of Fast Lyapunov Indicator (FLI), from the numerical integration of variational equations. In this paper, we present maps of stability that we realized in different dynamical configurations, and in particular a couple of ones standing for some representatives cases of operational or disposal orbits in the GTO and MEO regions. We analyze them in terms of detection of resonance areas, and we provide some comparisons between maps obtained from merely numerical or semi-analytical approaches.

Delisle, J. B., IMCCE, Paris (France), Dissipation in planar resonant planetary systems

Close-in planetary systems detected by the Kepler mission present an excess of period ratios that are just slightly larger than some low order resonant values. This feature occurs naturally when resonant couples undergo dissipation that damps the eccentricities. However, the resonant angles appear to librate at the end of the migration process, which is often believed to be an evidence that the systems remain in resonance. Here we provide an analytical model for the dissipation in resonant planetary systems valid for low eccentricities. We confirm that dissipation accounts for an excess of pairs that lie just aside from the nominal period ratios, as observed by the Kepler mission. In addition, by a global analysis of the phase space of the problem, we demonstrate that these final pairs are non-resonant. Indeed, the separatrices that exist in the resonant systems disappear with the dissipation, and remains only a circulation of the orbits around a single elliptical fixed point. Furthermore, the apparent libration of the resonant angles can be explained using the classical secular averaging method. We show that this artifact is only due to the severe damping of the amplitudes of the eigenmodes in the secular motion. Joint work with Laskar, Correia, Boué. Ref.: Delisle, Laskar, Correia, Boué, 2012, A&A, 546, A71

Diacu, F., University of Victoria (Canada), The N-body problem in spaces of constant curvature (invited talk)

The goal of this talk is to derive the gravitational N-body problem in spaces of constant curvature, to explain its importance, and to present some qualitative results.

Di Ruzza, S., Università di Pisa (Italy), Determination of the rotation state of Mercury by the on-board camera in the BepiColombo mission

The rotation experiment is an important task of the ESA BepiColombo space mission to Mercury. It is aimed at determining the rotation state of the planet, namely the obliquity and the libration in longitude, by using a high resolution on-board camera which is looking at the planet surface. The main idea of this work is to combine range and range-rate tracking from Earth to the Mercury Planetary Orbiter (MPO) together with the optical measurements performed by the camera, solving for all the significant parameters in a global least squares fit. It turns out that, thanks to a suitable definition of angular observables, it is possible not only to improve the knowledge of the rotation state of Mercury, but also to improve the orbit determination of the MPO with respect to the case of tracking data alone. Moreover, we will also be able to determine a geodetic network of landmarks on the Mercury surface.

Di Salvo, A., NEXT Ingegneria dei Sistemi SpA (Italy), Local time of node selection criteria for optical satellites in Sun-Synchronous Orbits

Joint Work with L. Faggioli (SpaceDys). The goal of this paper is to identify the criteria for selecting the local time of node of SSOs for optical remote sensing missions, completing a work previously presented by the authors. SSOs, guaranteeing high latitude accessibility and nearly constant illumination conditions over target areas, are typically selected for EO by optical instruments. The local time of passage to the node is a key parameter to be assessed to maximize observation opportunities over the area of interest throughout the year considering suitable on-ground illumination conditions and cloud cover statistics, and to maximize mission lifetime. Once detected the initial conditions, parametric analysis were performed firstly on LTAN/LTDN values and successively introducing solar zenith angle acquisition constraints, to evaluate how their variation affects the coverage and the mission lifetime; open data on cloud cover statistics contributed in the detection of the most fitting node values. Simulations were performed by using the SW STK 10 taking benefit from the new feature on parallel computing which allows reducing the duration of the computation.

Duering, M., University of Strathclyde (United Kingdom), Manoeuvring strategies for quasi-periodic trajectories

The libration point regions in the Sun-Earth and Earth-Moon systems are considered for ambitious space concepts involving long-duration crewed operations by space industry and agencies. It is required for such projects to cope with regular in-space operations, rendezvous, docking activities. The centre manifold existing within the vicinity of the libration points provides a variety of natural periodic and quasi-periodic orbits suitable for such proximity operations. This includes, but is not limited to halo, Lyapunov and quasi-halo orbits. In general, quasi-periodic trajectories can be described as two-dimensional invariant tori, and it is preferable to regard them directly as invariant object, covering any trajectory on its surface. A parametric representation reveals the structure of a torus and enables a discretisation of the torus which is used to implement and derive manoeuvre strategies and phasing considerations. In this paper manoeuvres are introduced to change the phasing of a spacecraft on a torus. Furthermore, amplitude changes, therefore transfers from one quasi-periodic trajectory to the other, are studied. Analytically derived single manoeuvre transfers are known from the linear Lissajous motion. The linear Lissajous motion is a decoupled motion in x-y and z-direction. In-plane phases and amplitudes relate to the motion in the x-y plane, whereas out-of-plane parameters describe the motion in z-direction. The linear analysis showed that at a particular time only one feasible phase or amplitude jump is possible utilising a single manoeuvre. In the in-plane case the manoeuvre do not instantly send the spacecraft onto the final orbit, but onto its stable manifold with the effect that the spacecraft asymptotically reach the final trajectory. In the out-of-plane case a phase change is only possible at a particular time when the initial and final trajectory intersect. After applying a manoeuvre the spacecraft continues its motion directly on the final orbit with a transfer time equal to zero. The analytic solutions show that amplitude or phase changes can be performed in two ways allowing a single manoeuvre. Quasi-periodic trajectories at the Earth/Moon libration point EML2 are computed and classified by their energy and their two system frequencies. Feasible phase changes either by direct or manifold transfers are investigated and compared with the linearised solution. Two-manoeuvres are used to construct the manifold transfers. A small manoeuvre to depart towards the stable manifold together with a backward integration is applied, and the initial orbit position is targeted after applying this first manoeuvre, the second one is conducted after arriving at the initial trajectory. For the direct case the algorithm search for intersections between the initial and final trajectory. The parametric torus functions enable to choose the final and initial states for this process for desired amplitudes and phases. This analysis details and expands the understanding of the natural dynamics and points out the knowledge and advantages gained from the structure of the torus and how their parametric representation supports manoeuvre implementations. For the case of a vehicle visiting an exploration gateway station on a halo orbit around EML2 the gained knowledge is applied to study feasible transfers and the associated fuel expenses from an arbitrary initial orbit to the invariant torus.

Dvorak, R., University of Vienna (Austria), New results on the three-Trojan problem

Three planets in the 1:1 Mean motion resonance are in stable configuration for different mass ratios. We explain the analytical approach and show some numerical results.

Efthymiopoulos, C., Academy of Athens (Greece), Analytical invariant manifolds and the convergence of the hyperbolic normal form

The computation of invariant manifolds around unstable periodic orbits is a subject with many new applications in astrodynamics and celestial mechanics. Starting with a review of the theories of Moser, Ozorio de Almeida and co-workers, and Giorgilli, we will discuss the convergence properties of the hyperbolic normal form series, i.e. series allowing to compute analytically the invariant manifolds of unstable periodic orbits. In the case of analytic symplectic 2D mappings, the domain of convergence extends to infinity along the invariant manifolds. As will be shown by specific examples, this allows to compute many non-trivial features of the homoclinic tangle using only series. In the Hamiltonian case, on the other hand, the domain of analyticity of the hyperbolic normal form has a finite extent along the invariant manifolds. We explain the origin of this difference between mappings and Hamiltonian flows. We also present a new method applicable in the latter case, which allows to extend the analytical computation of the invariant manifolds over an arbitrarily large length using only series. Finally, we discuss how the above results are generalized in the case of 4D mappings (or Hamiltonian systems of three degrees of freedom), around simply, doubly, or complex unstable periodic orbits.

Eggl, S., IMCCE - Observatoire de Paris (France), The NEOShield project: a comprehensive approach to asteroid mitigation

The meteor descending over Russian Chelyabinsk on February 15th 2013 has provided a preview of the potential havoc even relatively small Near Earth Objects (NEOs) can wreak. It is, thus, imperative to develop strategies for early an detection and a possible deflection of larger NEOs. Started in 2012, the NEOShield project, a prestigious international collaboration under European leadership encompassing industrial, university level as well as national research facilities, is aimed at providing comprehensive mitigation mission scenarios. Asteroid deflection is challenging problem. This contribution will provide a brief summary of the NEOShield project's results regarding state-of-the-art deflection scenarios. Joint work with D. Hestroffer, W. Thuillot, D. Perna, A. Barucci and A. Harris.

El Moutamid, M., Paris Observatory (France), Study of mean motion resonances in the Elliptical Three Body Problem

We investigate the dynamics of two bodies orbiting a massive central body in a common plane, near a first order mean motion resonance m+1 :m. The average equations of motion provide a system with two critical resonant angles which corresponds to the Lindblad and corotation mean motion resonances. The aims of this talk are : (1) to distinguish the two kinds of resonances when considering the restricted problem (when the mass of one of the two bodies is equal to zero). (2) to discuss the integrability of the two-degree of freedom system when the two critical angles are present. In the case of a Keplerian central potential the integrability of this system stems from the existence of a second integral of motion, besides the Hamiltonian. We show that this second invariant is a modified version of the Jacobi constant, where the orbital eccentricity of the two bodies is replaced by the relative eccentricity between the two orbits. When the central potential is not anymore Keplerian (due for instance to the oblateness of the central body), then the differential orbital precession of the two bodies destroys that modified Jacobi constant. (3) to rescale the restricted problem, so that it depends upon two parameters only : the distance between the two resonances and the disturbing body. While the problem is integrable when the distance is zero, we show numerically that a chaotic motion appears when the distance is small and different from zero. For large distances, we derive the solution using adiabatic invariance arguments (joint with Stéfan Renner, Bruno Sicardy).

Farnocchia, D., JPL/Caltech (USA), The strange case of asteroid (3908) Nyx

The trajectory of Near-Earth asteroid Nyx presents some anomalies. In particular, radar observations in 2004 showed unusually high residuals corresponding to a significant deviation from the predicted orbit. To shed light on these anomalies, we investigate three potential causes: 1) incorrect astrometric treatment; 2) collision with a small asteroid; 3) Yarkovsky effect.

For the astrometric treatment we apply a rigorous statistical scheme that removes star catalog biases, gives suitable weighting according to the observatory performances, and handles possible correlation among observation residuals. The occurrence of a collision is analyzed by looking for a statistically significant instantaneous delta-v satisfying the least squares principle. For the Yarkovsky effect we use a one-parameter formulation and seek evidence of the Yarkovsky related orbital drift in the fit to the observational dataset.

Farrés Basiana, A., Université de la Bourogne (France), Low-Thrust minimum time Earth-Moon transfer

We have considered the minimum time control problem in the Earth-Moon system. Our goal is to find minimum time transfer trajectories for a low-thrust propulsion system, between a circular Low Earth Orbit (LEO) around the Earth to a circular orbit around the Moon. We will consider the Earth-Moon Restricted Three Body Problem (RTBP) as a model adding the control parameter for a fixed thrust, and eventually include the gravitational effect of the Sun as a periodic perturbation using a restricted Bicircular model. We will discuss the controllability of the system and use shooting methods based on the Pontryagin Maximum Principal (PMP) to find optical control schemes. We will use homothopies with respect to different parameter in the model such as the maximum thrust magnitude to find such trajectories. Finally, we will try to give a description of the topology of the problem from a dynamical point of view.

Féjoz, J., Université Paris-Dauphine (France), Remarks on KAM theory (invited talk)

I will sketch a general set up for proving many classical and less classical theorems in KAM theory, through Moser's normal form of vector fields.

Ferraz-Mello, S., Universidade de Sao Paolo (Brasil), Tidal perturbations of the rotation of the Moon. The creep tide approach (invited talk)

The creep tide theory (Ferraz-Mello, CeMDA 2013, ArXiv astro-ph 1204.3957) was extended to include the spatial components of the motions. The cumbersome algebraic manipulations of this extension were overcome by the adoption of a numerical approach allowing applications to the actual more complex problems of planetary dynamics. This new approach allowed us to introduce the perturbations by a third body and consider the rotation of the Moon. The Moon is one of the best observed celestial bodies and the comparison of the predictions of the theory to observations may validate the theory and/or point out for the need of improvements. Particularly, the results for the tidal components of the physical libration of the Moon have been compared to the values determined from the Lunar Laser Ranging measurements (Williams et al. JGR 106, 27933, 2001). The comparison to observed effects related to the main solar perturbations - Annual equation, Variation and Evection - and to the reduction to the ecliptic shows partial agreement. Some of them can be explained only if the Moon's tidal dissipation is smaller than indicated by current values adopted for Q.

Fusco, G., Università dell'Aquila (Italy), Platonic polyhedra and chaotic motion in the N-body problem in the case of strong force (invited talk)

We let R be the group of rotations of one of the platonic polyhedra. We show that, in the case of strong force, in the class of motion of $N = |R|$ equal masses $u_r, r \in R$, that satisfy the symmetry condition $u_r(t) = ru_I(t)$, there exist chaotic motions. I is the identity in R.

Galan Vioque, J., Universidad de Sevilla (Spain), Symmetric horseshoe orbits in the general planar five-body problem

We introduce the horseshoe orbits in the general planar problem of five-bodies, for the case of four equal masses. We give some results concerning the periodicity for certain type of symmetric orbits and, using the software AUTO, determine the initial conditions of these orbits by means of solving a boundary value problem. We also show numerically the relation between these orbits and some homographic solutions. Joint work with Abimael Bengochea and Ernesto-Perez-Chavela.

Gales, C., Al. I. Cuza University of Iasi (Romania), A cartographic study of satellite and space debris dynamics

Due to gravitational and nongravitational perturbations, man-made objects (satellites and space debris) exhibit very complex orbits. Responsible for long term variations of space debris orbital elements are the Earth's oblateness, the lunar and solar gravitational attractions, the solar radiation pressure, the atmospheric drag and other small perturbations. Moreover, in vicinity of a resonance, comprehended as commensurability between the orbital period of man-made objects and the period of Earth's rotation, the predictability of orbits becomes problematic. On time scales of interest for mission planning, the interaction between resonant tesseral harmonics and lunisolar perturbations produces a chaotic response in orbital elements. The effect is enhanced for high area to mass ratio objects. Understanding overall orbital evolution of satellites and space debris is essential for maintenance and control strategies, as well as for space debris mitigation. In this work, for families of simulated Low Earth Orbits (hereafter LEO), Medium Earth Orbits (hereafter MEO) and Geostationary Earth Orbits (hereafter GEO), the global dynamics is investigated numerically by computing the Fast Lyapunov indicator (hereafter FLI), which provides an efficient tool to study the stable and chaotic behavior of a dynamical system. Our model includes the main effects, namely the gravitational influence of the Earth and the oblateness potential, the attraction of the Sun and Moon, the effect of the solar radiation pressure, while for LEO we consider in addition the atmospheric drag. The problem is approached by using both the analytical expansion method and by integrating directly the equations of motion. In the former case, we use a reduced Hamiltonian model based on an averaging process, the Earth's gravitational potential as given by the EGM2008 model and a suitable expansion in Legendre polynomials. By numerically computing the FLIs, a cartography of the main resonances is performed. The results are validated by integrating directly the equations of motion. This work is in collaboration with Alessandra Celletti.

Galiazzo, M., University of Vienna (Austria), V-types asteroids: impacts and close encounter with Terrestrial Planets

V-types asteroids are spread from the Main Belt to the inner Solar System. They can have many close encounters and eventually impacts with Terrestrial Planets. Our study will have a statistical approach in the investigation on their close approach to the planets, using gravitational and non-gravitational forces (i.e. the Yarkovsky effect). We will also consider the possible influence effect of three most massive asteroids in the Main Belt.

Giancotti, M., Università di Roma 'La Sapienza' (Italy), Families of Periodic Orbits in Hill's Problem with Solar Radiation Pressure

The motion of a spacecraft close to a small solar system body can be approximated with Hillś problem. This implies that the central mass is negligible with respect to that of the sun and that the distance to the sun is much greater than the others at play. The task of locating families of periodic solutions in such dynamics has been accomplished in several previous efforts. In this work we use a simple modification of the 3-dimensional Hilĺs equations of motion to account, besides the small bodyś gravity, also for the presence of solar radiation pressure. We apply numerical continuation and bifurcation theory to explore the changes of these orbit families when the radiation pressure parameter and the orbitś Jacobi constant are varied. We then compare the properties of a number of families and perform stability and bifurcation analysis on them.

Haghighipour, N., University of Hawaii (USA), Effects of Secular Resonances on the Formation of Terrestrial Planets

The formation of the terrestrial planets of our solar system is among the most intriguing problems of celestial mechanics and planetary cosmogony. Models of terrestrial planet formation have been successful to produce planets in the range of Venus and Earth. However, they have failed to produce Mars and Mercury analogs. The giant planets, especially Jupiter and Saturn play a crucial role in this process and are the main determinants of the final size, composition, and dynamical state of terrestrial bodies. The mean-motion and secular resonances due to these objects are key factors in the onset, development, and final orbital architecture of terrestrial plants. We have developed a new model of terrestrial planet formation that is capable of forming Mars, and addresses the effects of resonances, in particular Nu5, Nu6, and Nu16 on the evolution of the disk and the formation of the inner bodies in a comprehensive and multi-step approach. Results indicate that in disks where the surface density in the outer regions is less steep, the scattering effect of Nu6 is enhanced implying that terrestrial planet formation in such disks will be prolonged, the final planets will be smaller, however their water contents will be larger. Our model includes a new and sophisticated treatment of the collisions of planetesimals, which can account for the increase in the iron/silicate ratio from Mars to Mercury, and explains the formation of Mars as a natural consequence of the appearance of a local mass-depleted region in the protoplanetary disk.

Haus, E., Università di Roma 'La Sapienza' (Italy), Asymptotic behavior of an elastic satellite with internal friction

We study the dynamics of an elastic body whose shape and position evolve due to the gravitational forces exerted by a pointlike planet. The main result is that, if all the deformations of the satellite dissipate some energy, then under a suitable nondegeneracy condition there are only three possible outcomes for the dynamics: (i) the orbit of the satellite is unbounded, (ii) the satellite falls on the planet, (iii) the satellite is captured in synchronous resonance i.e. its orbit is asymptotic to a motion in which the barycenter moves on a circular orbit, and the satellite moves rigidly, always showing the same face to the planet. The result is obtained by making use of LaSalleś invariance principle and by a careful kinematic analysis showing that energy stops dissipating only on synchronous orbits. We also use in quite an extensive way the fact that conservative elastodynamics is a Hamiltonian system invariant under the action of the rotation group.

Hestroffer, D., IMCCE, Paris (France), Science of Solar System Objects with Gaia (invited talk)

The ESA space mission Gaia that will be launched at the end of this year 2013 will provide high precision astrometry and spectro-photometry of a large number of asteroids. The data acquired over the 5 years mission duration, possibly combined with ground-based observations, will enable many valuable improvements in the dynamics of main belt asteroids and Near Earth Objects as well as other small bodies of the Solar System. I will describe the mission operation, and some of the expected scientific impacts and outcomes.

Iorfida, E., University of Surrey (United Kingdom), Modelling mid-course correction of interplanetary trajectory

In the past 50 years the scientists have been developing and analysing methods and new algorithms, that optimise an interplanetary trajectory according to one or more objectives. Within this field, in 1963 Lawden proposed the primer vector theory and defined some necessary conditions that characterise an optimum trajectory. In particular the optimality regards the fuel consumption and it is achieved with respect to one or more potential intermediate impulses in a three body problem context. A novel approach to this theory, has been developed. It is based on a symplectic integrator and it simplifies the complexity of the current algorithm used to develop the theory of Lawden.

Kholshevnikov, K., St.Petersburg University (Russia), How precise is the epicyclic theory of planetary motion?

According to the widely spread opinion the epicycle model of planetary motion elaborated by Hipparchus–Ptolemy–Kopernik was cumbersome, and had a low precision. But a bunching of epicycles was originated by the absence of the statistical analysis of observations rather than by properties of the theory itself. Here we have established the following properties of the epicycle model under the condition of the optimal choice of its parameters. - Arbitrary continuous motion on a finite time-scale (on the infinite time-scale in case of almost-periodicity) can be presented to any desired degree of precision. - Motion of the Earth (Sun) can be presented by means of 2 circles to the precision higher than reached by Tycho Brahe. - Motion of Mars can be presented by means of 6 circles to the precision higher than reached by Tycho Brahe. - Visible motion on celestial sphere demands two times less number of circles.

Knezevic, Z., Astronomical Observatory, Belgrade (Serbia), A New Approach to Classification of Asteroids into Families

In view of the fast increase of the number of asteroids with accurately determined orbits as well as of the expected accelerated rate of this increase in the near future, it becomes more and more challenging to maintain and improve a classification of asteroids into families. The standard classification procedures, like Hierarchical Clustering Method (HCM) suffer from the problems like too dense background preventing the reliable determination of Quasi Random Levels, chaining affecting the membership assignment, and similar, and new approaches are needed to assess these problems. We developed such a new approach by combining the advantages of the standard procedure and its novel application. Our work is based on the large catalog of the high accuracy synthetic proper elements (available from http://hamilton.dm.unipi.it/astdys), containing data for more than 300.000 numbered asteroids with no limit in eccentricity and inclination. By selecting from the catalog much smaller number of large asteroids (below limiting magnitude between 14 and 15, depending on the semimajor axis), we first identify a number of so-called core families; to these, by using a newly adapted single-step HCM procedure, we attribute the next layer of smaller objects, thus completing the first step of the identification process. In the second step, we remove all the already identified family members from the catalog, and reapply the HCM to the rest. The results from the two steps are finally analyzed and merged to form final families. There are two kinds of output involved here: the already known families expanded by adding new members (small, recently discovered asteroids), and previously unknown families, identified for the first time, consisting mainly of small asteroids. We present here the detailed statistics of the output (number of identified families, known and unknown, percentage of family members), and discuss advantages of the new approach.

Kosenko, I., Russian Academy of Sciences (Russia), Dynamics of a Spacecraft Tethered to the Primary in the Restricted Elliptic Three-Body Problem

We consider motions of a space tethered system in the framework of planar elliptic restricted three-body problem. The spacecraft is attached to the smaller primary by a tether of variable length. The goal of the study is to examine the control laws for the tether length that keep the tetherś orientation with respect to the primaries. Among the discovered steady state motions there are two types of collinear configurations and two types of oblique ones. Stability of the system is studied analytically and numerically; several criteria of stability are used and compared. The conditions when the tether is stretched are identified for all steady-state configurations. The system in study is shown to possess both regular and chaotic behavior; the dynamical chaos growing from vicinity of separatrix with the increase of tether length is illustrated by the Poincaré iterated maps.

Laskar, J., IMCCE, Paris (France), Long time integrations of the Solar System (invited talk)

Long time integrations of the planetary motion in the Solar System has been a challenging work in the past decades. The progress have followed the improvements of computer technology, but also of improvements in the integration algorithms. This quest has led to the development of high order dedicated symplectic integrators that have a stable behavior over long time scales. As important in the increase of the computing performances is the use of parallel algorithms that have divided the computing times by an order of magnitude. Integrating the equation of motion is only a part of the work. One needs also to determine precise initial conditions in order to ensure that the long time integration represent actually the motion of the real Solar System. Once these steps are fulfilled, the main limitation in the obtention of a precise solution of the planetary motion will be given by the chaotic nature of the Solar system that will strictly limit the possibility of precise prediction for the motion of the planets to about 60 Myr.

Lemaitre, A., University of Namur (Belgium), The shadowing effects in the long term dynamic of space debris (invited talk)

We present an accurate symplectic integration scheme to numerically propagate space debris orbits over long periods of time. Among the perturbations that influence the motion, the solar radiation pressure plays an important role especially on debris characterized by high area-to-mass ratios. In this case, Earth's shadow crossings cannot be neglected. Hence we propose an innovative method that successfully models shadow crossings and does not break the symplectic properties of our propagator. Both cylindrical and conical shadows are considered. We show that the cylindrical model is only a poor approximation of the more realistic conical model, especially for high area-to-mass ratios. Thanks to both numerical and semi-analytical techniques, we then explain how shadow crossings are responsible for large periodic deviations from the initial condition. Finally an analysis is presented to highlight the strong influence of shadow crossings on the stability of high area-to-mass space debris located around the geostationary altitude.

Lhotka, C., Università di Roma 'Tor Vergata' (Italy), On the generalization of Pealeś formula

We present recent results about the generalization of Pealeś formula to higher order harmonics of the gravitational potential in the spin-orbit problem. The generalized formula is useful to understand the interior of celestial objects like Moons, planets of our solar and extra-solar planetary systems. We provide possible applications and recent results.

Libert, A.S., University of Namur (Belgium), Extension of the Laplace-Lagrange theory for the secular evolution of extrasolar systems

We investigate the effects of the proximity to a mean motion resonance (MMR) on the secular evolution of a two-planet system. If the system is near a MMR, the frequencies of the quasi-periodic flow given by the Laplace-Lagrange Hamiltonian are quite different from the true ones, and our study clearly shows that the approximation to order two in the masses describes more accurately their secular evolution than the usually adopted first order one. Moreover, this approach takes into account the influence of the mean anomalies on the secular dynamics. Using a high-order expansion in Poincaré variables, we introduce action-angle coordinates and compute analytically the long-term evolution of the Keplerian elements. Finally, we set up a criterion to discriminate between three categories of systems: (i) secular systems, (ii) systems near a MMR, (iii) systems really close to or in a MMR. A similar analytical study for these last systems is also discussed. Joint work with M. Sansottera.

Locatelli, U., Università di Roma 'Tor Vergata' (Italy), Sitnikov problem revisited: a new KAM approach based on the MacMillan integrable approximation (invited talk)

The Sitnikov problem is a very well studied ẗoy modelïn Celestial Mechanics. Having 1+1/2 degrees of freedom, it is very simple; nevertheless, it shows some interesting features from a pedagogical point of view. In the present talk, it will be shown that new results can be obtained if we make some suitable preliminary work, so to expand the initial Hamiltonian in the action-angle coordinates related to the integrable approximation given by the MacMillan problem. In particular, the proof of the existence of arbitrary large quasi-periodic oscillations will be sketched. All the results are based on a joint work with A.G. Castriotta, C. Lhotka and R.I. Paez.

Majorana, A., Università di Catania (Italy), Numerical solutions of gravitational Boltzmann-Poisson model for asteroids or planetary rings.

The gravitational Boltzmann-Poisson model is considered. It is a self-consistent system of the Boltzmann kinetic equation and the Poisson equation, describing the motion of a self-gravitating ensemble of randomly colliding particles. Here, the collision operator is replaced by a simple Bhatnagar-Gross-Krook (BGK) relaxation term. The force term of the Boltzmann equation is related to the total gravitational potential, which is determined self- consistently from the Poisson equation. This model was also used to study the stability of Saturnś rings. A discontinuous Galerkin (DG) finite element method for approximating the Boltzmann-Poisson model is employed. The method has the advantage of flexibility for arbitrarily unstructured meshes, with a compact stencil and, coupled with explicit and nonlinearly stable high order Runge-Kutta time discretization, allows to find time-depending solutions with great accuracy.

Mako, Z., Hungarian University of Transilvania (Romania), Some statistical properties of Weak Stability Boundary

This presentation provides a study of the stable and unstable regions around the smaller primary in the framework of the spatial elliptic restricted three-body problem. First we investigate the rate of symmetry of the stable region and we determine the correlation between the initial inclination and the measures of stable and unstable regions for different systems. For example we put in evidence that the rate of symmetry of the stable regions for the Sun-Mercury system is of 95% for prograde and 92% for retrograde motion respectively. Finally, we derive the probability density functions, the mean values and the variances to characterize the stable and unstable regions.

Marchesiello, A., Università di Roma 'La Sapienza' (Italy), Bifurcations in Hamiltonian systems around symmetric resonances

We investigates the dynamics of two degrees of freedom Hamiltonian systems around symmetric resonances. With this we mean Hamiltonian dynamical systems close to an equilibrium, invariant with respect to reflection symmetries in both configuration variables, in addition to the time reversion symmetry, and with quadratic part with unperturbed frequencies close to a resonant ratio. Systems with these properties naturally appear in Galactic Dynamics to describe the orbital structure of elliptical galaxies. The analysis is performed combining three different mathematical tools: Perturbation Theory, Normal Forms Theory (in particular, ¨detunedïnormal forms) and Singularity Theory. We study the most relevant resonances and related bifurcations providing quantitative predictions, in the form of energy threshold values, which determine the appearance of the main periodic orbits (joint work with Giuseppe Pucacco).

Milani, A., Università di Pisa (Italy), Predictions for Chaotic Dynamics: 15 years of Impact Monitoring (invited talk)

The debate on the possibility of predicting the impact of an asteroid on Earth was sparked in March 1998 by the 1997 XF11 case. After the demonstrated failure of the linear approach, given the known inefficiency of pure MonteCarlo methods, Line Of Variation (LOV) methods were introduced in 1999. They use the differentiable structure of a manifold of solutions, selected to represent the range of possible outcomes on the Target Planes of the future close approaches. This has allowed the setup of information services providing lists of asteroids with Virtual Impactors, for which there is need of follow up observations. A moderate number of intermediate close approaches can be handled, providing a reliable detection of low probability impacts. However, reliable detection does not imply accurate determination of the initial conditions leading to impact. The attempts of pushing the same method beyond a predictabilty horizion, typically located at about 100 years after the last observations, have shown the limitations of the current methods and suggested a search for new algorithms. Reverting to MonteCarlo for few special cases is possible, because of current computer performances. The alternative could be relying less on the local linearization of tangent maps, that is essentially using LOVs (and possible 2-D analogous) as topological manifolds, with local densifications replacing the use of the tangent map. These algorithms can be used both with a 6-D phase space of intiial conditions and with a 7-D space including a semiempirical Yarkovsky parameter, to accomodate the contribution of model uncertainty (see Chesley, this meeting, for a discussion of Impact Monitoring with non-gravitational perturbations).

Mingotti, G., University of Strathclyde, Glasgow (United Kingdom), Combined Invariant Manifolds and Low-Thrust Propulsion Trajectories to Capture Asteroids

Joint work with Dr.Joan-Pau Sanchez Cuartielles and Prof. Colin McInnes. A method to capture Asteroids incorporating low-thrust propulsion into the invariant manifolds technique is presented in this work. Assuming that a tugboat-spacecraft is in a rendez-vous condition with the selected Asteroid, the aim is to take the joint spacecraft-Asteroid system to a target periodic orbit around a libration point in the Sun-Earth restricted three-body problem. In detail, low-thrust propulsion is used to bring the joint spacecraft-Asteroid system from the initial condition to a point belonging to the stable manifold associated to the final periodic orbit: from here onward, thanks to the intrinsic dynamics of the physical model adopted, the flight is purely ballistic. Dedicated capture sets are introduced to exploit the combined use of low-thrust propulsion with stable manifolds trajectories, aiming at defining feasible first guess solutions. An optimal control problem is then formulated to refine them in a more accurate dynamical model. This approach enables a new class of missions, whose solutions are not obtainable neither through the patched-conics method nor through the classic invariant manifolds technique.

Pilat-Lohinger, E., University of Vienna (Austria), Solar system analogs and the habitability of the Earth

Discoveries of more than 860 extra-solar planets illustrate a diversity of these planetary systems. However, none other system than ours is known to host a habitable planet like the Earth. Assuming that solar system like configurations are the most favorable ones for a habitable Earth, we show in this study the influence of the architecture of a planetary system on the habitability, where we analyze the region between 0.6 and 1.6 AU in the solar system.

Pitjeva, E., Russian Academy of Sciences (Russia), Numerical ephemerides of planets and their natural satellites of IAA RAS and their using for scientific research

The EPM ephemerides (Ephemerides of Planets and the Moon) of the IAA RAS originated in the 1970ś and have been improved since that time. The dynamical model of the planetary part of the EPM ephemerides includes mutual perturbations from the major planets, the Sun, the Moon, 301 large asteroids and 21 trans-Neptunean objects (TNO), from massive asteroid and TNO rings, as well as the lunar physical libration and the solar oblateness. The EPM2011 ephemerides were fitted to about 680,000 observations of different types (1913-2011). EPM ephemerides are the basis for the Russian Astronomical and Nautical Astronomical Yearbooks, are used in the GLONASS program, and for determination of physical parameters (asteroids masses, planet rotation, topography), the GM_{Sun} and its secular variation, the relativistic parameters, the upper limit on mass of dark matter in the solar system. Moreover, numerical ephemerides of the 22 main planet satellites were constructed taking into account mutual perturbations of satellites, perturbations from planets and the Sun, and figures of planets.

Pucacco, G., Universitá di Roma "Tor Vergata" (Italy), Geometric analysis of bifurcations in symmetric resonances

We present a general analysis of the bifurcation sequences of periodic orbits in general position of resonant Hamiltonian normal forms with reflection symmetries. The low-order cases 2:2 and 2:4 show rich structures that can be investigated with singularity theory and geometric methods.

Roig, F., Observatorio Nacional, Rio de Janeiro (Brazil), Transport of V-type asteroids from the Vesta family

We review some recent results on the long term dynamical evolution of V-type asteroids that point to their origin as fugitives from the Vesta family. Within the possible transport mechanisms, the origin of Near Earth V-type asteroids is addressed, and we provide observational evidence of the first V-type asteroids identified among the Mars crossers population.

Rosaev, A., OAO NPC Nedra (Russia), Stability of binary system on highly eccentric orbit

Problem of stability satellite of planet at highly eccentric heliocentric orbit have a number of various applications. One of them: extrasolar planets have a large eccentricity. It is known, that possibility to capture on a satellite orbit is decreased with primary orbit's eccentricity increasing. It means, that satellites of planet on eccentric orbit are less stable. It is naturally to suggest, than some of satellites will be loss during eccentricity growth. In result of our studying, the dependence of orbital energy on external eccentricity is derived for binary system. It is shown, that infinitesimal mass satellite is more stable than binary system with compatible masses. Our computations are illustrated by numeric modeling of binary destruction at eccentricity increase. Finally, we can conclude, that extrasolar planets may have significantly smaller satellites, than planets in our solar system. Moreover, dependence on eccentricity makes restriction on Giant planets migration in our Solar System.

Rossi, A., IFAC/CNR (Italy), Collision risk and disposal strategies for Global Navigation Satellite Systems (invited talk)

The Medium Earth Orbit region, home of the operational Global Navigation Satellite Systems, is becoming more and more exploited with the advent of the European Galileo and the Chinese Compass constellations. The sensitive applications of the navigation satellites and the absence of any natural sink mechanism, such as the atmospheric drag, call for a careful debris prevention policy able to preserve the environment, avoiding in the future the problems now already faced by the LEO and GEO regimes. Disposal strategies for the spent spacecraft and upper stages have to be carefully designed and analyzed, taking into account the complex dynamics of this orbital region, in view of the collision risk and of the expected maneuver rate for collision avoidance in the next decades. The results of a large set of simulations with different algorithms will be shown and compared, highlighting the most convenient global disposal strategies, in particular for the European Galileo constellation.

Sansottera, M., University of Namur (Belgium), Lower dimensional elliptic tori in planetary systems via normal form

This is a joint work with Ugo Locatelli and Antonio Giorgilli. We give a constructive proof of the existence of lower dimensional elliptic tori in nearly integrable Hamiltonian systems. In particular, we focus on the existence of such invariant tori for the planetary problem. In a previous work, see [5], we adapt the Kolmogorov normalization algorithm, which is the key element of the original proof scheme of the KAM theorem, to the construction of a suitable normal form related to an invariant elliptic torus for a planetary system. Moreover, an explicit calculation of the torus for the Sun-Jupiter-Saturn-Uranus system has been performed and the resulting orbits have been found to be in agreement with those obtained by direct numerical integration. Let us remark that elliptic tori may be used as a refined extension of elliptic keplerian orbits in the Lagrange-Laplace secular theory. In this work, we support with rigorous convergence estimates our semi-analytical algorithm. With respect to previous works on the same subject (see, e.g., [3] ,[6], [1] and [2]) we make use of a non-resonance condition weaker than the commonly used Diophantine one. Our condition transports in the KAM framework a similar one that has been introduced in [4] for the Poincaré-Siegel problem.

REFERENCES

[1] L. Biasco, L. Chierchia and E. Valdinoci: "Elliptic two-dimensional invariant tori for the planetary three-body problem", Arch. Rational Mech. Anal., 170 , 91-135 (2003).

[2] L. Biasco, L. Chierchia and E. Valdinoci: "N-dimensional elliptic invariant tori for the planar (N+1)-body problem", SIAM J. Math. Analysis, 37, 1560-1588 (2006).

[3] L. H. Eliasson: "Perturbations of stable invariant tori for hamiltonian systems", Annali della Scuola Normale Superiore di Pisa - Classe di Scienze, 15, 115-147 (1988).

[4] A. Giorgilli and S. Marmi: "Convergence radius in the Poincaré-Siegel problem", DCDS Series S, 3, 601-621 (2010).

[5] M. Sansottera, U. Locatelli and A. Giorgilli: "A Semi-Analytic Algorithm for Constructing Lower Dimensional Elliptic Tori in Planetary Systems", CeMDA, 111, 337-361 (2011) DOI: 10.1007/s10569-011-9375-x.

[6] J. Pöschel: "On elliptic lower dimensional tori in Hamiltonian systems", Math. Zeitschr., 202, 559-608 (1989).

Serra, D, Università di Pisa (Italy), A semi-analytic theory to estimate the uncertainty of a space mission Gravity Science experiment

The aim of the work is to develop a semi-analytic theory in order to study the uncertainty the gravitational potential zonal harmonic coefficients of a planet can be recovered with, starting from Doppler observations of a spacecraft orbiting it. Moreover, the uncertainty is shown to depend only on the geometry of the orbit. We also obtain estimations of the surface gravity anomalies, that enable us to predict in which regions of the planet the gravity field is recovered more accurately. The theoretical study has been implemented in a software and tested on simulated observations of the Juno spacecraft around Jupiter. The results we obtained are in agreement with the previsions: the gravity field looks well recovered only in the 11 deg N - 34 deg N latitude belt, which corresponds to the latitudes of the Gravity Science orbits' perijoves.

Souami, D., SYRTE - Observatoire de Paris - Univ. Paris 6 (France), Testing the universality of a law for the spacing of planetary systems

The study of exoplanetary systems is of fundamental interest in 21st century astronomy, though the question of planetary spacing has been present since ancient Greece. In our work, we investigate the universality of a "Titius-Bode" type-law for the mean distance of planets around their stars, as was previously done in the works of S. Albeverio & al., L. Nottale, and J. Laskar. Within the framework of a stochastisation hypothesis (J. Cresson 2011), the dynamics of a protoplanetary nebula naturally leads to a universal structuration law depending on one constant. Using the Kepler catalogue for exoplanets we statistically test, through a specific regression missing data stochastic algorithm, this universality on multi-planetary systems. Joint work with : J. Cresson ; C. Biernacki & F. Pierret.

Sousa-Silva, P., Instituto Tecnologico de Aeronautica - ITA (Brasil), Practical Stability Boundaries around L4,5 in the spatial R3BP

We consider the problem of stability around the triangular equilibria of the spatial Restricted Three-Body Problem. It is known that Nekhorosev-like estimates of diffusion indicate the local existence of practical stability domains around L4,5 and numerical evidence shows that these regions can be quite large depending on the mass parameter. We show the role played by several codimension-one manifolds in the determination of the sharp stability boundaries around L4,5. In particular, for small values of the mass parameter we identify two different situations: (i) the stable and the unstable hyperbolic manifolds of the center manifold of L3 account for the confinement of trajectories, similarly to that happens in the planar R3BP; (ii) the stability boundaries are due to the invariant manifolds of a biparametric family of hyperbolic two-dimensional tori associated to a family of periodic orbits near L4,5. Joint work with Carles Simó and Maisa Terra.

Spoto, F., Università di Pisa (Italy), Shadowing Lemma and Chaotic Orbit Determination

In 1987, during the Urey Prize Lectures, Wisdom conjectured that the knowledge gained from measurements on a chaotic dynamical system grows exponentially with the time span covered by the observations. This conjecture is not always true. We apply the Shadowing Lemma to the orbit determination of the standard map in the chaotic and regular case. We show that simultaneous estimation of initial conditions and of parameters appearing in the dynamical equations does not result into exponentially decreasing accuracy, until the bad conditioning horizon is reached. On the contrary, if the only solve parameters are the initial conditions, then they can be estimated with accuracy increasing exponentially in time provided they are in the center of the observed interval.

Suvakov, M., University of Belgrade (Serbia), Slaloms: A Special Order of Periodic Solutions to the Three-body Problem

I present eleven new periodic solutions with zero angular momentum in the Newtonian planar three-body problem with equal masses. These solutions belong to a special örder(type) of families of three-body periodic motions, which I call slaloms, and that can be described as higher powers of the "figure-eight" solution in the sense of the topological classification method. These new solutions fall into three new geometric-algebraic classes [1]. Among them, one solution is remarkable, possessing a special dynamical symmetry. Numerical integration over a million of syzygies presents evidence of its stability.

Sweatman, W., Massey University (New Zealand), Orbits near equal-mass four-body central configurations

This study explores equal-mass four-body orbits passing close to a quadruple central configuration. Locally, these orbits are approximated as a perturbation from the central configuration orbit. This proceeds in a similar fashion to the approach used for three-body systems previously. A number of terms appear in the perturbation. The dominant perturbation term determines how the system evolves as it leaves the neighbourhood of the quadruple central configuration.

Teofilatto, P., Università di Roma 'La Sapienza' (Italy), Homoclinic and Heteroclinic Connections through Isomorphic Mapping

This paper is concerned with a topological study of the transfer trajectories to the Moon, with particular interest to the low energy trajectories that allow performing (long-term) lunar captures and to trajectories that exhibit homoclinic and heteroclinic connections. In general, the third body trajectory oscillates, in the sense that the spacecraft passes continuously from the neighborhood of the Earth to the region in proximity of the Moon (and viceversa). A fundamental topological theorem stated by Conley is focused on the location of capture trajectories in the phase space, which includes all the dynamical information on the spacecraft state (defined by its position and velocity). In this work this fundamental theoretical assertion is used together with an original cylindrical three-dimensional representation of trajectories. This cylindrical representation is associated with an isomorphism between actual coordinates (of position and velocity) and transformed coordinates. For a given energy level, the (stable and unstable) manifolds associated with the Lyapunov orbit around L1 are computed and represented in cylindrical coordinates as tubes that emanate from the (transformed) periodic Lyapunov orbit. Sections of these tubes are considered. A relevant number of points lying on these sections are selected, and the corresponding positions and velocities are assumed as initial states and then numerically propagated, to find how long each trajectory remains in the neighborhood of the Moon, with the final intent of evaluating the capture duration as a function of the initial state. The cylindrical representation is then employed to detect homoclinic connections. The analysis included in this paper, based on isomorphic mapping, allows finding the geometrical locus that corresponds to these connections. In fact, each manifold is associated with a tube in the transformed space. As a result, the geometrical locus associated with homoclinic connection s is represented as the intersection between distinct tubes. The existence of these connections suggests an interesting interpretation, and together corroboration, of Conley's assertion on the topological location of lunar capture orbits. An analogous analysis is dedicated to the study of heteroclinic connections.

Terracini, S., Università di Torino (Italy), Symbolic Dynamics for the N-centre problem at negative energies (invited talk)

It is part of the mathematical folklore that dynamical systems featuring many nonlinear interactions should be subject to chaotic behavior and possess complex dynamics. On the other hand, for systems appearing in nature, this is far to be a rigorous statement and, even more, lacks a rigorous proof, specially when we leave behind the perturbative setting. We consider the planar N-centre problem, with a family of homogeneous potentials including the gravitational Kepler potential. Our strategy is to attack the problem of constructing complex trajectories problem by the use of global variational methods. We prove the existence of infinitely many collision-free periodic solutions with negative and small energy, for any distribution of the centres inside a compact set. The proof is based upon topological, variational and geometric arguments. The existence result allows to characterize the associated dynamical system with a symbolic dynamics, where the symbols are the partitions of the N centres in two non-empty sets.

Valsecchi, G.B., IAPS-INAF (Italy), A numerical exploration of periodic orbits close to that of the Moon

The Saros is an eclipse cycle of 223 synodic months; its study allowed to find that the lunar orbit is very close to a set of 8 periodic orbits (POs) of the restricted circular 3-dimensional Sun-Earth-Moon problem, differing from each other for the phases, whose duration is 223 synodic months. These POs are not the longest ones that can be found close to the lunar orbit; according to Poincaré there should be infinitely many POs, of longer and longer duration, that get closer and closer to the actual lunar motion. The longer POs are arranged, in the eccentricity-inclination plane, in a characteristic pattern, that is a deformation of the arrangement, in frequency space, of the frequency ratios of the POs themselves. Exploiting this, we have set up a numerical procedure to find POs, whose durations are multiples of the synodic month, and have used it to make a systematic exploration of the POs in the Sun-Earth-Moon problem over the entire eccentricity-inclination plane.

van der Weg, W., University of Strathclyde (United Kingdom), Earth-Sun L1 and L2 to Moon transfers exploiting natural dynamics

Joint work with Massimiliano Vasile. The design of transfers from Earth-Sun libration L1 and L2 points towards the Moon using a combination of natural dynamics, low-thrust and impulsive manoeuvres is examined in order to dispose or extend mission lifetime of a spacecraft in orbit around the L1 and L2 Sun-Earth points. The residual on board propellant at the end-of-life in combination with natural dynamics can be used to move the spacecraft towards the Earth-Moon system in an attempt to extend its operational lifetime. Disposal by impact upon the lunar surface is also a possibility. Weak capture by the Moon can allow the spacecraft to be inserted into a variety of lunar orbits, depending on what level of residual v is available. Weak capture at the Moon is studied by method of lunar survivability maps where a range of initial conditions for the spacecraft approaching the Moon is propagated forward in time under the effect of the gravitational pull of the primary bodies to evaluate the number of complete revolutions before impact or escape. From this, promising regions in the state space can be studied in more detail using a complete dynamic model to assess the influence of perturbations such as solar radiation pressure. Backward propagation is then used to ensure that long term capture is achievable from the Earth-Sun L1/L2 region.

Verheylewegen, E., University of Namur (Belgium), Secular Resonances in Mean Motion Commensurabilities for the internal Uranian satellites

Joint work with A. Lemaitre. Voyager II mission that explored the Uranian system and its satellites in 1986, did not reveal important information about the internal satellites. These inner satellites present particular misunderstood dynamics. The few references about the understanding of their evolution are focused on the dynamics of Mab (Kumar et al., 2011) or the instability of Cupid, Belinda, Cressida and Desdemona (Duncan and Lissauer (1996), French and Lissauer (2012)). We focus on the couple Cressida-Desdemona which is near the commensurability 3:1 with the main satellite Miranda, each one on a different side of the resonance. Based principally on the semi-numerical approach of Morbidelli and Moons (1993), we study the secular resonances inside the mean motion commensurability and test several scenarii of the evolution of those two satellites, explaining their present positions, in two and three dimensions. A similar work could be performed on a 4th order mean motion resonance between the couple Cupid-Belinda and Miranda.

Voyatzis, G., University of Thessaloniki (Greece), Vertical instability and excitation of inclination during planetary migration.

We consider a two-planet system, which migrates under the influence of dissipative forces. It has been shown that for the planar case, migration leads to resonant capture after an evolution driven by the families of periodic orbits (Lee & Peal, 2002; Ferraz Mello et al, 2003; Hadjidemetriou & Voyatzis, 2010). In three dimensions (3D) resonant capture also takes place and in some cases excitation of planetary inclinations has been observed (e.g. Thommes & Lissauer, 2003; Libert & Tsiganis, 2009). In this work we show that in the three dimensions, the planetary migration also follows paths in phase space, which are associated with resonant capture and families of periodic orbits. Excitation of inclinations appears when the planar families, which drive the initial stage of planetary migration, become vertically unstable. Conclusively, we can predict when inclination increases during the migration by computing the position of vertically unstable periodic orbits and th e families of 3D periodic orbits that bifurcate from them. Joint work with K. Antoniadou and K. Tsiganis.

Waldvogel, J., ETH, Zurich (Switzerland), Regularization of the symmetric four-body problem by elliptic functions

Consider 4 point masses $m_k > 0$ at positions $\mathbf{x}_k(t) \in R^2,\ k = 1, 2, 3, 4$, moving under Newtonian forces and satisfying the symmetry relations $m_1 = m_3,\ m_2 =$

m_4, $\mathbf{x}_1(t) + \mathbf{x}_3(t) = 0$, $\mathbf{x}_2(t) + \mathbf{x}_4(t) = 0$ at all times t. This system, referred to as the *Caledonian Four-Body Problem,* has been extensively studied B.A. Steves, A.E. Roy, and many others. Binary collisions can occur as single collisions between m_1 and m_3 or between m_2 and m_4. Also, simultaneous collisions (m_1, m_2) and (m_3, m_4) or (m_1, m_4) and (m_2, m_3) can occur. Regularization according to Levi-Civita is possible in every case. A single coordinate transformation involving elliptic functions is able to regularize every binary collision.

Zhou, L.-Y., Nanjing University (China), Co-orbital motion in the outer solar system

We present the results of our investigation on the dynamics of co-orbital objects on the orbits of Uranus and Neptune. We will reveal the dominant resonances involved in the motion, analyze the dynamical effects of the inclination on the orbital stability. We will investigate the behaviours of co-orbitals when the orbital configuration of the solar system was different from the current, and check the role played by the co-orbitals in the orbits transferring of small celestial objects and in the material delivery in the early stage of the solar system.

2 Posters

Alessi, E.M., IFAC-CNR (Italy), Periodic orbit tour for planetary system exploration

The increasing interest in the exploration of planetary systems as small scale solar system models motivates for innovative mission analysis approaches. The Jupiter system in particular presents a number of targets with a relevant scientific importance. In this work we will consider coupled CR3BP dynamics to identify a set of periodic orbits for the cyclic exploration of the Galilean moons. A periodic orbit offers a unique way to have a ballistic path that can be suited for the exploration of each satellite. In addition, by considering a set of small (few m/s) impulsive maneuvers the CR3BP dynamics can be used to move from one system to another, thus changing the exploration target with a minor effort. The choice of the most favorable periodic orbits, their exploitation for the Galilean satellites observation and the identification of the proper maneuvers to move from a periodic orbit to another will be presented.

Ammar, M., University of Annaba (Algeria), Some generalized Lienard systems: their limit cycles via averaging theory

we give the maximum number of limit cycles of some generalized Lienard systems of the form x' = y2k+1; y' = x2k+1+f(x)y2n+1; where k and n are non-negative integers, f(x) is a polynomial of degree m, epsilon is a small parameter, x = x(t); y = y(t), and the dot denotes derivative with respect to the variable t.

Antognini, F., ETH Zürich (Switzerland), Conditions on the existence of periodic orbits in a dissipative spin-orbit model

The dissipative spin-orbit model of celestial mechanics is investigated. Explicit conditions for the existence of $(p, q)-$ periodic orbits and estimates on the measure of the basins of attraction of stable periodic orbits are discussed for any $q \in N$. Furthermore applications to the majority of satellites in the solar system for $(1, 1)$ resonance, and to the Sun-Mercury case are given.

Antoniadu, K., Aristotle University of Thessaloniki (Greece), Resonant periodic orbits in three dimensional planetary systems

We consider the general spatial three body problem (TBP) and study the dynamics of planetary systems consisting of a Star and two inclined Planets, which evolve into mean motion resonance (MMR). We introduce the model used to simulate three dimensional planetary systems, discuss main concepts of periodic orbits and present two Schemes of analytic continuation, i) from 3D-restricted to 3D-general TBP and ii) from 2D-general TBP to the spatial one. Finally, we present both planar and spatial families of symmetric periodic orbits of systems locked in every MMR observed up to date, i.e. the dominant 2/1, 3/1, 3/2, 4/1, 4/3 and 5/2. Long term stability analysis has revealed that many stable periodic orbits reach mutual inclination up to 50° - 60°, which may be related with the existence of real planetary systems trapped in the above mentioned MMR.

Baidolda, F., IMCCE, Observatoire de Paris (France), The influence of planetary motion on the solar activity

We investigated the solar cycles with long term and the possible relationships with planetary motions. The solar cycles are derived from long-term observations of the relative sunspot number. The relationships between multi-timescale solar periodic modes and the planetary motions will help us to understand the essential natures and prediction of solar activities. The closely connection between the mid-term periodic modes of solar activity and the planetary motions may imply that it can be applied to predict the solar activity in the far future.

Bazso, A., University of Vienna (Austria), Librational motion in the spatial R3BP

We report the results of numerical investigations on the stability of librational motion in the restricted three-body problem for variations in the mass-ratio and eccentricity/inclination of the Trojan. Several resonances between the librational frequencies occur, especially secondary resonances. Applications are possible in the Solar system and to Trojan-type exoplanets in binary star systems.

Colombo, C., University of Southampton (United Knigdom), Space debris monitoring from space-based elliptical orbits

Joint work with A. Di Salvo (NEXT), C. McInnes (University of Strathclyde), F. Paolillo (NEXT). Currently ground-based telescopes allow observing 10 cm size debris in GEO and MEO, while using radar facilities it is possible to detect LEO objects down to 1 cm. An optical space-based surveillance network could be employed to cover this gap of observation of small debris at high altitudes also taking advantages of: 1) the use of specific baselines between satellites, 2) observing out of Earth's atmosphere; 3) optimisation of debris lighting condition. This paper analyses the possibility of employing elliptical-orbits for space-based observation as an efficient alternative to standard circular orbits. The secular effects of solar radiation pressure and the Earth's oblateness are exploited to maintain the spacecraft on a family of "Heliotropic" or "Anti-heliotropic" orbits, i.e., with a Sun-pointing apogee or perigee respectively, so that enhanced coverage is provided during daylight hours for visible light imaging. The orbital elements are traded and identified to meet increased debris coverage in the most populated orbit regions and to maximise the detection capabilities; a comparison with figure of merits from high altitude circular SSOs is also performed.

Compère, A, University of Namur (Belgium), The two-body interaction potential in the STF tensors formalism: an application to binary asteroids

Nowadays the scientific community considers that more than a third of the asteroids are double. A large proportion of these systems are bodies with similar masses and irregular shapes. Their study requires then a full body-full body approach. Several models have been built for the full two-body problem and compared to each other. However, a nice tool, the symmetric trace free (STF) tensors formalism, developed for binary stars or planetary systems, has not yet been applied to binary asteroids. We present here a comparison of the two-body interaction potential in the STF tensors formalism with the classical models in the case of double asteroids.

Eggl, S., IMCCE - Observatoire de Paris (France), Determining Habitable Zones in Binary Star Systems

One of the most ambitious aims of exoplanetary research is the discovery of potentially habitable planets around stars other than our Sun. Since the majority of stars in the solar neighborhood belong to binary and multiple systems, such environments cannot be ignored in the search for a second Earth. Yet, gravitational perturbations alter planetary orbits in such systems, so that considerable variations in insolation occur. We offer an analytic framework to calculate habitable zones in binary star systems encompassing both, dynamical and radiative aspects. Consequently we show that most of the nearby double stars with well known orbital parameters have regions where an Earth-like planet can retain liquid water on its surface.

Fantino, E., Universitat Politecnica de Catalunya - ETSEIAT (Spain), Characterization of highly inclined orbits for Earth observation, Communications and Navigation

The issue of characterizing orbits for coverage of high latitudes for Earth Observation, Communications and Navigation applications purposes is here considered. Traditional solutions include the Molniya and Tundra orbits (at critical inclination with period of 12 and 24 h, respectively), with high eccentricity and argument of perigee of 270° so as to set the apogee at high latitudes. Recently, a geo-synchronous, highly eccentric polar orbit, called Tundra polar orbit, has been proposed because its 90° inclination eliminates the precession of the ascending node and its 24 h period allows a single, long contact per orbit with the ground station. In this study we perform an extensive analysis of highly inclined orbits in a wide range of orbital elements: we characterize their geometry and evolution with a high precision model of the gravity field, supplemented by an adequate representation of other environmental accelerations. The final aim is to reach a deeper understanding of the available orbit options and to select solutions for further analyses in terms of key parameters for EO, TLC and Navigation mission scenarios (joint work with A. Di Salvo (NEXT)).

Farres Basiana, A., Université de la Bourgogne (France), Families of Periodic and Quasi-Periodic motion for Imperfect Solar Sails around asteroid

It is well known that solar radiation pressure (SRP) plays an important role in the dynamics around asteroids as magnitude is comparable to gravitational attraction. Hence, the systematic use of SRP to propel a satellite via specialised reflecting areas, such as solar sails, can give rise to new and interesting mission concepts. Our goal is to study the dynamics of a non perfectly reflecting solar sail near an asteroid, having as reference model the Augmented Hill 3-body problem (AH3BP). This is a Sun-asteroid-satellite Hill problem, with the asteroid considered as a point mass, that includes the effect of SRP due to the solar sail. To model the solar sail's acceleration we will include both reflectivity and absorption of the sailś material. We will carry out a dynamical study of the AH3BP in terms of fixed points, families of periodic and quasi-periodic orbits and their invariant manifolds, for a range of solar sail parameters for reflectivity and absorptivity.

Galan Vioque, J., Universidad de Sevilla (Spain), Bifurcations of periodic solutions from the center of mass in a generalized Sitnikov problem

We consider the Sitnikov problem with N primaries bodies with equal mass moving around the origin in the plane x, y as generalized solutions of the Lagrange problem. We call this problem the Generalized Sitnikov Problem. This special restricted N+1-body problem can be reduced to the Sitnikov problem with an appropriate positive parameter λ. According to the number of bodies we proved the existence (or non- existence) of a finite number (or infinite number) of symmetric families of periodic solutions that bifurcate from the equilibrium z = 0 (center of mass of the system) at certain values of the eccentricity. We provide also numerical continuation results concerning the stability and bifurcation behaviour of the branches.

Georgakarakos, N., T.E.I. of Central Macedonia (Greece), Habitable zones for planetary systems with gas giants: an analytic approach.

Today, more than 880 planets are known to revolve around stars other than our Sun.Since the detection of planets with comparable size to that of the Earth finally lies within our grasp, an issue of great scientific as well as public interest is whether Earth-analogues may be found orbiting within the habitable zone. Looking at the current observational evidence in and beyond our Solar System, it seems most likely that the presence of gas giants does not preclude the existence of terrestrial planets in the same system. However, the gravitational interactions between possible terrestrial companions and the gas giants can influence the extent of a systemś habitable zone. In this work, we determine analytically the limits of the habitable zone for an Earth-like planet in the presence of a gas giant. An application of the method to a sample of currently known exoplanetary systems is also provided.

(Joint work with S. Eggl, E. Pilat-Lohinger and B. Funk) .

Hestroffer, D., IMCCE, Paris (France), Orbits of binary asteroids using a Markov chain Monte Carlo technique

We present a novel method of orbit computation for resolved binary asteroids. The method combines the Thiele-Innes-van den Bos method with a Markov chain Monte Carlo technique (MCMC). The classical Thiele-van den Bos method has been commonly used in multiple applications before, including orbits of binary stars and asteroids; conversely this novel method can be used for the analysis of binary stars, and of other gravitationally bound binaries. The method requires a minimum of three observations (observing times and relative positions - Cartesian or polar) made at the same tangent plane - or close enough for enabling a first approximation. Further, the use of the MCMC technique for statistical inversion yields the whole bundle of orbits possible, including the most probable one.

In this new method, we make use of the Metropolis-Hastings algorithm to sample the parameters of the Thiele-van den Bos method, that is the orbital period (or equivalently the double areal constant) together with three randomly selected observations from the same tangent plane. The observations are sampled within their observational errors (with an assumed distribution) and the orbital period is the only parameter that has to be tuned during the sampling procedure. We run multiple chains to ensure that the parameter phase space is well sampled and that the solutions have converged. After the sampling is completed we perform convergence diagnostics. The main advantage of the novel approach is that the orbital period does not need to be known in advance and the entire region of possible orbital solutions is sampled resulting in a maximum likelihood solution and the confidence regions. We have tested the new method on several known binary asteroids and conclude a good agreement with the results obtained with other methods. The new method has been implemented into the Gaia DPAC data reduction pipeline and will be used in the long-term processing of the Gaia data in particular to confirm the binary nature of a suspected system, and for deriving the mass determination of the binary system (joint work with D. A. Oszkiewicz, P. David)

Kosenko, I., Russian Academy of Sciences (Russia), On Equilibria of a Lunar Pendulum

It is known from everyday experience that an inverted pendulum is unstable. The same observation is also valid for the pendulum suspended to the Moon. However, for a ̈very, very long ̈pendulum it is not the case: if the pendulum length exceeds certain value, then the pendulum extended along the Earth - Moon straight line is stable in sense of Lyapunov. It means, that there exist other, unstable equilibria in the Earth - Moon orbital plane. It turns out, that there exist also equilibria located outside the orbital plane. These equilibria were verified to be unstable in the secular sense. The necessary conditions of spatial stability for librations/rotations of the Lunar pendulum moving in the orbital plane are also under investigation. An alternation of stable and unstable motions depending on libration amplitude or angular velocity of rotation was found numerically. Similar alternation of stability for the satellite in the circular orbit planar oscillations is well known (Markeev, Sidorenko & Neustadt).

Kovacs, T., Konokly Observatory, Budapest (Hungary), Stability chart of the L4 and L5 points in the elliptic-restricted three-body problem

By using Hillś equations and the energy-rate method, an analysis of the stability map of the elliptic-restricted three-body problem is performed. Regions of the $\mu - e$ parameter plane are described numerically and related to the resonant frequencies of librational motion. Stability and instability can therefore be obtained by analysing the two independent frequency modes depending on system parameters. The key role of the long period libration in determining the structure of the stability is demonstrated and also a stability mechanism is found that is responsible for extended lifetime of the test particle in the unstable domain of the stability map.

Kuznetsov, E., Ural Federal University, Ekaterinburg, (Russia), Orbital evolution of the Earth's satellites in resonance regions with resonance splitting effect

Orbital evolution of the Earth's satellites in resonance regions is investigated. Resonance splitting effect takes into account. Numerical modeling is used. The model of disturbing forces takes into account the main perturbing factors. There are the gravitational field of the Earth, the attraction of the Moon and the Sun, the tides in the Earth's body, the direct radiation pressure, taking into account the shadow of the Earth, the Poynting-Robertson effect, and the atmospheric drag. Period of time reaches to 240 yr. Locations and sizes are estimated for resonance regions with resonance splitting effect. Orbital evolution is investigated for GEO, HEO, GNSS orbits, and orbits surrounding these regions. Area-to-mass ratio varied from small values corresponding to satellites to big ones corresponding to space debris. It is considered orbital evolution in resonance regions, capture and exit from resonance and passage through resonance.

Li, J., Nanjing University (China), A study of the high-inclination population in the Kuiper belt.

The dynamical stability and evolution of the Kuiper belt objects (KBOs) with high inclinations up to 90 degrees are systematically explored. With special emphasis on their high inclinations, we have provided new insights into the dynamics of the (2:3, 1:2 and other high order) mean motion resonances and secular resonances, the peculiar orbital distribution of currently KBOs, and ways to reconcile the origin/evolution of these objects with our current understanding of the formation of the outer solar system.

Marini, V., University of Trento (Italy), Adiabatic chaos in the spin-orbit problem

We provide evidences that the angular momentum of a symmetric rigid body in a spin-orbit resonance can perform large scale chaotic motions on time scales which increase polynomially with the inverse of the oblateness of the body. This kind of irregular precession appears as soon as the orbit of the center of mass is non-circular and the angular momentum of the body is far from the principal directions with minimum (maximum) moment of inertia. We also provide a quantitative explanation of these facts by using the theory of adiabatic invariants, and we provide numerical applications to the cases of the 1:1 and 1:2 spin-orbit resonances (joint work with G. Benettin and M. Guzzo).

Noullez, A., Observatoire de la Cote d'Azur (France), Global dynamics of a lunar orbiter using Frequency Analysis

authors: S. Tzirti (1), A. Noullez (2), K. Tsiganis (1)
(1) Aristotle University of Thessaloniki (Greece)
(2) Observatoire de la Côte dAzur (France)

In this work we apply a new Frequency Analysis method (FA) to the problem of secular dynamics of low lunar orbiters, in the framework of high degree lunar gravity models. The use of the FA allows for an efficient exploration of large grids of initial conditions and extended phase-space domains, thus providing a global view of the secular dynamics. Here, we restrict our study to models of degree 3, 7 and 10 in the spherical harmonics expansion of the Moon's gravity field, in which the main terms of the Earth's gravity are added. Using frequency and amplitude maps, we can identify the dominant perturbations. We confirm the dominant role of the 7th degree zonal term for low altitudes, and show the main effect of non-axisymmetric terms on the location of periodic orbits. Finally, we show how, using FA on a finer grid of orbits around a suitably chosen 'first guess', we can obtain the initial conditions for long-term stable, nearly-periodic polar solutions.

Acknowledgements: This research has been co-financed by the European Union (European Social Fund - ESF) and Greek national funds through the Operational Program Education and Lifelong Learning of the National Strategic Reference Framework (NSRF) - Research Funding Program: Heracleitus II. Investing in knowledge society through the European Social Fund.

Olikara, Z., Institut d'Estudis Espacials de Catalunya (Spain), Disposal techniques for spacecraft in libration point orbits

In this study we investigate end-of-life trajectories for spacecraft in orbit about the Sun-Earth L1 and L2 libration points. A plan for decommission is often required during the mission design process. While collinear libration point orbits are unstable causing spacecraft to naturally depart their vicinity, certain outcomes are preferable to others. Given the limited fuel available towards the end of a spacecraft's mission, invariant manifold theory will be used to study the dynamics driving the motion. We initially consider two main classes of outcomes: long-term orbits that are nominally stable and orbits colliding with a solar system body. We seek to organize and compare the costs associated with these decommission possibilities by performing a parametric study. A set of baseline Sun-Earth libration point orbits, including both halo- and Lissajous-type orbits, will used as representative departure points.

Paez, R. I., Università di Roma 'Tor Vergata' (Italy), Exploring the marginal stability region in theplanar circular restricted three-body problem

The stability region around the Lagrangian points L4-L5 has been widely studied in the literature, both analytically and numerically. The analytical approaches are usually based on suitable normal forms (see, e.g., Giorgilli & Skokos, A&A, 1997) and aim to show the stability of asteroids (the Trojans). We designed a "new" semi-analytic approach based also on some ideas by Garfinkel (Astron. J., 1977): the Hamiltonian is expanded in Delaunay coordinates and a suitable average on the fast angle is performed. This allows us to construct (quasi) invariant tori that are far from Lagrangian points L4-L5. As an ultimate goal of our research project, we want to understand how to connect those tori with the stable/unstable manifolds emerging from L1-L2 with some (possible cheap) manoeuvres of a spacecraft. This can be important for station-keeping and observational purposes of a space mission in the Trojans region. The e-poster will show the current state-of-the-art of the project.

Paita, F., Institut d'Estudis Espacials de Catalunya (Spain), On the Cucker-Smale flocking model applied to a formation moving in a central force-field

The Cucker-Smale (CS) flocking model is an interacting particles control system where every element adjusts its dynamics according to a weighted average between its velocity and those of the other elements of the flock. Under this model, a rigid body configuration can be achieved exponentially fast for suitable initial configurations. Furthermore, as shown by J. Shen, if the dynamics of the formation is driven by the presence of a free willed leader then similar asymptotic results can also be obtained. In the present paper we extend the CS control law in the context of a multi-spacecraft system moving around a central body. Some new analytical results are given, as well as the results of the extensive numerical experimentations that have been done to evaluate the performances of the control law, with particular attention to its interaction with a central gravitational field. These performances have been evaluated mainly through the use of two indicators: the evolution of the relative spacecrafts distances and the total fuel expended to maintain the formation.

Pérez-Palau, D., Universitat de Barcelona (Spain), Jet Transport propagation of uncertainties for orbits around the Earth

In this paper we present a new tool to study the non-linear propagation of uncertainties for orbits around the Earth. The tool we introduce is known as Jet Transport and allows to numerically propagate full neighbourhoods of initial states instead of a single initial state with usual integrators. The description of the image neighbourhood is obtained in a semi-analytical way by means of polynomials in 6 variables. These variables correspond to displacements in the phase space from the reference point selected in an orbit as initial condition. The basis of the procedure is a standard numerical integrator of ordinary differential equations (such as a Runge-Kutta or a Taylor method) where the usual arithmetic is replaced by a polynomial arithmetic, in this way, the solution of the variational equations is obtained up to high order. The method is applied to the propagation of satellite trajectories and to obtain the images, and high order nonlinear descriptions, of uncertainty ellipsoids. The procedure can be specially adapted to the determination of collision probabilities with catalogued space debris or for the end of life analysis of spacecraft in Medium Earth Orbits. Joint work with G. Gómez and J.J. Masdemont.

Perozzi, E., Deimos Space, Madrid (Spain), The European NEO Coordination Centre (D. Koschny, G. Drolshagen (ESA ESTEC) E. Perozzi, E. Parrilla-Endrino, J. Correia de Oliveira (Elecnor Deimos) F. Bernardi, G. D'Abramo (SpaceDys) S. Weikert, R. Schneider (Astos Solutions) A. Tesseri, N. Biviano, B. Borgia (Serco) A. Milani (Universita' di Pisa) G. B. Valsecchi (INAF IAPS))

The design and the deployment of a NEO Coordination Centre able to rely on and exploit at best the European worldwide excellence in orbit determination, impact monitoring and asteroid physical characterization has been successfully achieved within the framework of the ESA Space Situational Awareness programme. The SSA NEO CC, located at ESRIN (Frascati, Italy), is organised as a dynamic three-layer structure, including a database, the related services and an interface (Web Portal) allowing interrogations of the database and as placeholder for additional services. The main data sources are NEODyS (as the authoritative source for NEO orbit characterization and impact monitoring), the Spaceguard Central Node Priority List (and related services) for coordinating NEO follow-up observations, and the Near-Earth Asteroid Research Node (EARN) as a repository of physical data. Access to these data and services (obtained via SLA) provides state-of-the-art information on the NEO hazard. The NEO Web Portal has been designed in order to guarantee a centralized access point to the data centre existing tools and facilities, allowing the search in those services through a user-friendly graphical interface. The Centre has been officially inaugurated on 22 May 2013 and Precursor Services operations are on-going. Major improvements of both the functionalities and the services are also foreseen: comets and fireballs are expected to enter the NEO database, thus encompassing all celestial objects which are likely to come in the vicinity or actually hit our planet. Thus the SSA NEO Data Centre has the potentiality to represent a unique facility in the worldwide NEO monitoring scenario, hosting data and services which are at present addressed by different institutions often being physically and logically separated. Please visit us at http://neo.ssa.esa.int

Pittich, E., Solovaya, N., Slovak Academy of Sciences, Bratislava (Slovak Republic), Motion of Pasiphaeś perijove

N. A. Solovaya (Sternberg State Astronomical Institute, Lomonosov Moscow Univerzity, Moscow, Russia); E. M. Pittich (Astronomical Institute, Slovak Academy of Sciences, Bratislava, Slovak Republic) The motion of the argument of perijove of the 8th satellite of Jupiter has been investigated. The dominant perturbations by the Sun to the satellite allow us to use the intermediate orbit, obtained by approximated solution of differential equations before transformation by the Zeipelś method. The orbit is non-Keplerian ellipse. The secular motion of the node, perijove, and essential periodic perturbations were taken into account. The retrograde motion demonstrates an interesting geometry of the satellitež orbit. The observe limits of the variations in the semi-major axis are 0.149¡a¡0.168 AU, eccentricity 0.177¡e¡0.675, and inclination 138.2¡i¡156.9 deg (Whipple et al., 1993). Using our theory we show that can be cases when the inclination and eccentricity have such values by which the circular motion of the argument of perijove becomes librating around 90 or 270 deg. Therefore it is not possible to speak about the mean velocity of the perijoveś motion. Taking into account the results of our previous work and results of other authors we can give following conclusions. The mean velocity of the motion of the ascending node is similar in all works. But the velocity of the motion of the argument of perijove is different. We suppose that it is not possible to speak about the mean velocity of the perijove of Pasiphae.

Plávalová, E., Slovak Academy of Science (Slovak Republic), Analysis of the motion of an extra-solar planet in a binary system

More than 10% of extra-solar (EP) planets orbit in a binary or multiple stellar systems. We investigated the motion of planets revolving in binary systems in the frame of the particular case of the three body problem. We produced the analysis of the motion an EP revolving in a binary system by following conditions; a)a planet in a binary system revolves around one of the components (parent star), b)the distance between the star's components is greater than between the parent star and the orbiting planet (ratio of these two distances is a small parameter), c)the mass of the planet is smaller than the mass of the star, but is not negligible. The Hamiltonian of the system without short periodic terms was used. Expanded in the terms of the Legendre polynomial and truncated after the second order term depending on the one angular variable. In this case the solution of this system was obtained and the qualitative analysis of motion was produced. We have applied this theory to real EPs and compared to the numerical integration. Analyses of the possible regions of motion are presented. It is shown that the cases of the stable and unstable motion of the EPs are possible. We applied our calculations to two binary systems hosting an EP and calculated the possible values for their insufficient orbital elements. For 16 Cyg Bb, there is a region between 44° and 46° for the inclination, and the value of the ascending node between 130° and 137° of the planet , or the inclination could have a value from 134° to 136° and the ascending node from 310° to 317°. For planet HD19994 b, to have a stable system, the value for the insufficient elements should be in the region of 62° to 68° for the inclination, and the value of the ascending node between 260° and 268° of the planet. Alternatively, the inclination of the planet also could have the value of 112° to 118° and the ascending node between 80° and 88°.

Rosaev, A., OAO NPC Nedra (Russia), Mean distance between orbits and search for minor planet catastrophic breakup

Minimal Orbit Intersection Distance (MOID) is an important parameter to study small bodies catastrophic destruction. But in a number of cases, orbital intersections not lead to two body collision. So, an addition criteria related with epoch of catastrophe is required. In a number of cases, mean distance between orbits (MOD) can be an addition parameter to study minor planets dynamical history. MOD can be determined as an average distance between two orbits in a finite numbers of points. We suggest select these points by special way. It is known, that in general, distance between orbits have 8 maximal and minimal values. It is natural to use these value for compute MOD. At epoch T of catastrophic disruption with small relative velocities of fragments, MOID and mean distance between orbits have a minimum. MOD is close to Lyapunov's characteristic exponent, which is a measure of divergence initially close trajectories. A series of numeric integration of 12 initially close orbits is done on time interval 270000 years for some real minor bodies. Results are discussed. It is confirmed, that in some cases minimal distance between orbits have a minimum, while mean distance continue to increase.

Sansottera, M., University of Namur (Belgium), Effective stability around the Cassini state in the spin-orbit problem

We investigate the long-time stability in the neighborhood of the Cassini state in the conservative spin-orbit problem. Starting with an expansion of the Hamiltonian in Andoyer-Delaunay canonical variables, we construct a high order Birkhoff normal form and give an estimate of the effective stability time in the Nekhoroshev sense. By extensively using algebraic manipulations on a computer, we explicitly apply our method to the rotation of Titan. We obtain physical bounds of Titan's latitudinal and longitudinal librations, finding an effective stability time greatly exceeding the estimated age of the Universe. In addition, we study the dependence of the effective stability time on three relevant physical parameters: the orbital inclination, i, the mean precession of the descending node of Titan's orbit, $\dot{\Omega}$ and the polar moment of inertia, C (joint work with Christoph Lhotka, Anne Lemaitre).

Shibayama, M., Osaka University (Japan), Variational proof of the existence of the super-eight orbit in the four-body problem

I will prove the existence of the Gerver's super-eight orbit by using the variational method. The difficulty of the proof is to eliminate the possibility of collisions. In order to solve it, I apply the scaling technique established by K. Tanaka.

Stefanelli, L., OCA - Université de Nice Sophia Antipolis (France), Resonances due to third body perturbations in the dynamics of MEOs

The dynamics of Medium Earth Orbits (MEO) sees nowadays a renewed interest because of the development of satellites constellations (GNSS), that raises the problem of parking orbits for satellites at end of life. Numerical evidence shows that the resonances related to the presence of a third body can affect the stability of MEO orbits. The goal of our work is to study the effects of resonances on the stability of MEO orbits, over long or very long term (hundreds of years). For orbits above 20,000 km altitude, the perturbation due to a third body (the Moon or the Sun) is not fully negligible, so we take into account the third body perturbation on the secular evolution of the angular variable of the satellite orbits, and thus of the resonant angle. We estimate numerically the evolution of the resonant inclination. We study the stability of some resonances analytically and numerically, and in particular the resonance associated to the operational inclination of the Galileo satellites.

Titov, V., Saint Petersburg State University (Russia), Some periodic orbits of general three body problem with vanishing angular momentum

The periodic solutions of general three body problem are found. The solutions under discussion are extension of well-known figure-eight orbit. Found orbits are described on the Euclide plane and on form sphere.

Todorovic, N., Astronomical Observatory of Belgrade (Serbia), Mapping the region of Pallas asteroid family by the Fast Lyapunov Indicator

The Fast Lyapunov Indicator stands out as one of the fastest numerical ways to detect the stability or chaoticity of an orbit. Moreover, the FLI is able to distinguish between strong and weak chaos, as well as between resonant or non resonant stable orbits. These properties allow the detection of the resonant geography for different systems, but in the past it was mainly applied to symplectic maps. However, despite its efficiency, the FLI has never been widely used to study dynamics of real objects in the Solar System. In this work we employed the FLI to better understand and analyze the dynamical characteristics in the region of Pallas asteroid family. Computing FLI for different sets of initial conditions, we where able to detect different dynamical regimes present in the region (joint work with Bojan Novakovic).

Turconi, A., Surrey Space Centre (United Kingdom), Efficient modelling of small bodies gravitational potential for autonomous approach

Asteroids are the next destination for space exploration and for improving our knowledge of the Solar System. Techniques to deal with their peculiar dynamical environment are important also for NEO hazard mitigation and for the possible exploitation of resources on these small bodies. The aim of the research is to use an approximated model of the gravitational potential, simple enough to be implemented and updated on board the spacecraft, in order to enable autonomous navigation in the vicinity of these bodies. The presence of equilibrium points in the dynamics of rotating asteroids is described and an a simplified model showing similar dynamical characteristics is presented. It is also analysed the influence of Solar Radiation Pressure at the typical location of those equilibrium points. Finally, using models with lower degrees of freedom, strategies for the generation and update of the approximated model are proposed.

Tureshbayev, A., Korkyt Ata Kyzylorda State University (Kazakhstan), Stability of libration points for photogravitational restricted three-body problem with two radiating masses

Studied stability of cloud clusters of micrometeorite particles and gas-dust matter in the binary star systems field. As a dynamic model we consider the photogravitational limited circular 3-body problem where 2 main bodies are radiating. It's carried out a non-linear stability analysis for triangular libration points and found the stability area in the configuration and parameters spaces. Stability is almost everywhere for the majority of the initial conditions for these points in the stability area, with the exception of points corresponding to resonances 3rd and 4th order. Shown for all resonances of 3rd order these points are unstable. We have proved stability of order 4 in some areas. Conditions of Arnold-Moser theorem are always satisfied in the stability region of the linear system for masses in intervals (0; 0,0079625269) and (0,3860630212; 0,5) .

Vienne, A., IMCCE - University of Lille (France), Stability of the quasi-satellites of the Earth

A quasi-satellite is an asteroid trapped in 1:1 resonance with a planet but it is not a Trojan (motion around L4 or L5) nor a 'horseshoe' (motion around L3, L4 and L5). This body has an eccentricity different from the planet so it turns around the planet in a retrograde way. But it can not be considered as a satellite because it is out the Hill' sphere. In the case of the Earth, these bodies are 'Near-Earth Objects' (NEO). So the study of the stability of these bodies is important because of the potential danger of them to the Earth. Here we present preliminary results in which we illustrate some characteristics of their motion found in literature on the few quasi-satellite of the Earth. We use the orbits computed numerically with EPOS (Pulkovo Observatory). We specially emphasize how the asteroids move from quasi-satellite orbits to horseshoe orbits (joint work with Olga Vasilkova, Cesar Gattano).

Vilhena de Moraes, R., UNIFESP (Brasil), Stability of the triangular libration points taking into account the light pressure

R.Vilhena de Moraes(1), J. K. Formiga(2), T. J. Stuchi(3), M. Alvarez Ramirez(4), J.E.F. Skea(5)

(1) UNIFESP - Universidade Federal de São Paulo, São José dos Campos, Brasil, rodolpho.vilhena@gmail.com (2) FATEC - Faculdade de Tecnologia, São José dos Campos, Brasil, jkennety@yahoo.com.br (3) UFRJ - Universidade Federal do Rio de Janeiro, Brasil, tstuchi@if.ufrj.br (4) UAMI - Universidade Autonoma do México Iàztapalapla, Mexico (5) UERJ - Universidade Estadual do Rio de Janeiro, Brasil

We discuss the state of art of three-body problem when an infinitesimal mass is affected not only by gravitation but also by light pressure from both of the primaries. This problem is usually called the photogravitational one. In contrast to the classical problem, both primary gravitating bodies radiate. The conditions for stability of a three-parameter family of the triangular libration points are obtained, in the absence of resonance, so as to study the effect of radiation in the stability. A retrospective chronological review of the previous results is given. The method used here to analyze the behavior of the stability of equilibrium points of nonlinear dynamical systems requires the normal form of the Hamiltonian. An analytical process to normalize Hamiltonian system is described.