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1. Dynamics of Extrasolar Planets (C. Beaugé)

The orbital fits of multi-planetary systems from radial velocity data has proved to be a complex task. In some cases, different orbital solutions provide similarly good fits, especially when two planets are near mean-motion resonances. Ferraz-Mello *et al.* (2005) and Goździewski *et al.* (2005) showed that the published best fits of systems *HD82932* and *HD160691* are dynamically unstable, and re-determined their orbital parameters with Monte Carlo and genetic algorithms. In both cases dynamically stable orbits were found with RMS similar to the published orbits. It was also shown that uncertainties in the stellar mass (FerrazMello *et al.* 2005) and the stellar jitter (Gozdziewski *et al.* 2005) can significantly affect the orbital determination. Ford (2005) used a Markov chain Monte Carlo technique to quantify the orbit uncertainties. For some planetary systems he found a strong correlation between the orbital elements and/or significant non-Gaussian error distribution in the parameter space. As a consequence, the actual uncertainties in the orbital fits can be much larger (or smaller) than those published.

Multiple-planetary systems in mean-motion resonances are relevant for their complex dynamics, but also for the inferences on a past planetary migration. To date there are at least four confirmed resonant systems: *GJ876*, *HD82943* and *HD128311* in the 2/1 commensurability, and *HD202206* in the 5/1. The two middle planets of *55Cnc* seem to be in the 3/1 mean-motion resonance, although there is some doubt on the orbital fits and more observations are necessary. The orbital fits of all these candidate resonant systems place the planets in an Apsidal Corotation Resonance (ACR): both the resonant angle σ and the difference in longitudes of pericenter $\Delta\varpi$ oscillate around a stationary value. Snellgrove *et al.* (2001) found that an ACR configuration similar to the fit of the *GJ876* planets could be explained via a smooth inward planetary migration from initially non-resonant circular orbits. Hadjidemetriou (2002), Hadjidemetriou & Psychoyos (2003), Beaugé *et al.* (2003) and Lee (2004) used numerical and analytical approaches to determine families of ACR in mean-motion resonances, particularly the 2/1 and 3/1, as a function of the planetary mass ratios, semi-major axes and eccentricities. Resonance capture under a wide range of migration mechanisms and the relationship between the ACR and migration has also been the subject of several studies (e.g. Lee & Peale 2002, Nelson & Papaloizou 2002, Papaloizou 2003, FerrazMello *et al.* 2003, Kley *et al.* 2005).

For non resonant planetary systems, Goździewski (2002), Goździewski & Konacki (2004) and Goździewski *et al.* (2005) mapped the phase space near several systems (*47 UMa*, *HD169830* and *HD160691*) and identified regions of stable and chaotic motion. Lee & Peale (2003) studied an octupole-level analytical model for secular motion of hierarchical systems such as *HD12661* and *HD168443*: contributions from nearby mean-motion resonances (up to high order) are significant for the dynamical evolution. Michtchenko & Malhotra (2004) presented a semi-analytical study with application to *Ups And*: the observed apsidal alignments are not secular resonances, but circulations around a center displaced from the origin. They identified the separatrix in the planar problem and found that the secular resonance is always located at very high eccentricities of both planets.

The existence of a large population of exoplanet very close to the star ($a \leqslant 0.1$ AU) and in quasi-circular orbits (the so-called "Hot Jupiters") raises many questions on the origin and also the orbital evolution and stability. Several works have analyzed the effects of tidal interaction with the primary (e.g. Pätzold & Rauer 2002, Sasselov 2003). Many unknown parameters must be assumed, including the rotation velocity distribution and evolution of solar-type stars, tidal energy dissipation factor, etc., (Ogilvie & Lin 2004, Dobbs-Dixon *et al.* 2004, Pätzold *et al.* 2004). It is possible that some of the Hot Jupiters are undergoing an infall towards the star (Pätzold *et al.* 2004) over time scales of the order of $10^8 - 10^9$ years. However, the dynamical models are still approximate and need to be improved. Furthermore additional perturbations, such as relativistic effects (Mardling & Lin 2002) or magnetic braking, may also need to be considered for some systems.

At least 20 planets have been detected in multiple stellar systems; for three of them the distance between stars is less than 20 AU: (*HD41004*, γ *Cephei* and *Gliese 86*). Although the orbits are sufficiently close to one of the primaries to assure dynamical stability, their formation process is still not well understood. Numerical simulations by Quintana *et al.* (2002) and Thébault *et al.* (2004) have shown that, contrary to previous beliefs, the presence of a secondary star does not necessarily inhibit planetary formation, may even accelerate the accretion process. In a gas-rich scenario, the secondary star may induce apsidal alignment of the planetesimals. Thus, although the individual eccentricities may be high, the relative impact velocities may remain bounded below the accretion threshold.

Other related problems have also been explored in the last few years. The stability of hypothetical terrestrial planets in the habitable zones of known planetary systems has been discussed in several papers (e.g. Jones & Sleep 2002, Cuntz *et al.* 2003, Menou & Tabachnik 2004, Érdi *et al.* 2004). The effects of mutual inclinations on the dynamics of resonant planets has also began to be considered (Thommes & Lissauer 2003, Veras & Armitage 2004, Ferraz-Mello *et al.* 2005), although the complexities in the dynamics introduced by the third dimension still need to be explored more thoroughly.

2. The dynamic shaping of the Trans-Neptunian belt (A. Morbidelli)

It is now evident that the orbital structure of the trans-Neptunian population is intimately related to the characteristics of Neptune's radial migration. The expansion of the orbit of Neptune due to the interaction with a disk of planetesimals has been studied in detail in Gomes *et al.* (2004): if the disk was massive (50 $M_\oplus$ or more, between 20 and 50 AU), Neptune should have migrated up to the outer edge of the disk. This raised the problem of why Neptune stopped at 30 AU. Two potential solutions have been identified in Gomes *et al.* (2004). Either (i) the planetesimal disk was truncated at ~ 30 AU, or (ii) the disk was extended, but its surface density was small enough that Neptune had to stop. In this latter case, the Kuiper belt beyond 35 AU would have preserved essentially all its pristine mass. We know that this is not true. The Kuiper belt's current mass is only $\sim$0.01 $M_\oplus$ Bernstein *et al.* (2004), less than one percent of the initial mass. Thus, the problem of Netpune's migration is intimately related to the problem of how the Kuiper belt lost its mass. In Gomes *et al.* (2004) all scenarios of dynamical depletion were

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rejected, because the planetesimals ejected from the Kuiper belt to Neptune-crossing orbit would have re-started Neptune's migration. Several problems with the scenario of mass depletion by collisional grinding were also pointed out. In addition, the most advanced of the collisional models showed that the total mass of the Kuiper belt could be reduced to few $0.01 M_\oplus$, only if a very low specific disruption energy Q_* is assumed; if more reasonable values of Q_* (similar to those obtained in hydro-code experiments Benz & Asphaug (1999)) are adopted, the final mass achievable in the collisional process has to be at least one tenth of the initial mass, namely about 1 $M_\oplus$ or more. Thus Gomes *et al.* (2004) concluded that the most plausible explanation for the current orbit of Neptune is that the planetesimal disk was truncated at about 30 AU. Several mechanisms have been proposed to truncate the planetesimal disk Ida *et al.* (2000) Weidenshilling (2003) Youdin & Shu (2002) Stone *et al.* (1998) Adams *et al.* (2004).

If the primordial edge of the massive proto-planetary disk was somewhere around 30 AU, then the *entire* Kuiper belt population –not only the scattered disk– had to form within this limit and be transported to its current location, presumably during Neptune's migration. Two mechanisms have been identified to push beyond the original disk edge a small fraction (of order 0.1%) of the disk's planetesimals, and to implant them on stable Kuiper belt orbits. As Neptune moved through the disk, it scattered the planetesimals with whom it had close encounters. Through multiple encounters, some planetesimals were transported outwards on elliptic, inclined orbits. A small fractions of these objects still constitute the scattered disk. Occasionally some scattered disk objects entered a resonance with a planet. Resonances can modify the eccentricity of the orbits. If decreased, the perihelion distance is lifted away from the planets; the sequence of encounters stops and the body becomes "decoupled" from Neptune, like a Kuiper belt object. If Neptune had not been migrating the eccentricity would have eventually increased back to Neptune-crossing values—the dynamics being reversible—and the sequence of encounters would have restarted again. Neptune's migration broke the reversibility, so that some of the decoupled bodies managed to escape from the resonances and remained permanently trapped in the Kuiper belt Gomes (2003). These bodies preserved the large inclinations acquired during the Neptune-encountering phase, and they can now be identified with the 'hot' component of the Kuiper belt population. A few scattered objects also reached stable Plutino orbits, with orbital properties comparable to those of the observed objects.

At the same time, while Neptune was migrating through the disk, its resonances 1:2 and 2:3 swept through the disk, capturing a fraction of the disk planetesimals. When the 1:2 resonance passed beyond the edge of the disk, it kept carrying its load of objects. Because the migration of Neptune was presumably not a perfectly smooth process, the resonance was gradually dropping objects during its outward motion. Therefore, the resonance disseminated its previously trapped bodies all along its way up to its final position at about 50 AU Levison & Morbidelli (2003). This explains the current location of the outer edge of the Kuiper belt. Because the 1:2 resonance does not significantly enhance the orbital inclinations, the bodies transported by the resonance preserved their initially small inclination and can now be identified with the 'cold' component of the Kuiper belt.

The transport mechanism described in Gomes (2003) also explains the origin of some of the extended scattered disk population, for $a > 50$ AU and perihelion distance $q \sim 40$ AU. These objects, barely beyond the limits of the scattered disk in perihelion distance, are a sort of continuation of the hot Kuiper belt beyond 50 AU. Conversely, there is a growing consensus that Sedna ($a = 495$ AU and $q = 76$ AU) and, possibly, 2000 CR_{105} ($a = 222$ AU, $q = 44.3$ AU) were put from the scattered disk onto their current orbits by a stellar encounter: Morbidelli & Levison (2004), Rickman *et al.* (2004).

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This emerging understanding of the Kuiper belt sculpting process has been recently perturbed by a new scenario of giant planet evolution, see Tsiganis *et al.* (2005) Gomes *et al.* (2005), to explain the origin of the cataclysmic Late Heavy Bombardment (LHB). This scenario still invokes a truncated planetesimal disk, thus requires that the Kuiper belt was pushed out from within the disk's original outer boundary. However, the migration mode of Neptune in this model was very different. Neptune's eccentricity was greatly excited during the LHB, while the planet was scattered outwards by encounters with Uranus and -possibly- Saturn. Neptune's eccentricity damped due to dynamical friction when the planet was already almost at 30 AU. The 'classical' migration, used in Gomes (2003) and Levison & Morbidelli (2003), started later and covered only a small radial distance range. Therefore, it will be necessary to study new transport mechanisms for the Kuiper belt objects in this new planet evolution framework.

3. Orbit determination for the next generation surveys (J. Virtànen)

Some of the major efforts in the solar-system research today are connected to the impending next generation surveys. Ground- and space-based projects such as Pan-STARRS, LSST, DCT, and Gaia coming operational within the next decade will change the nature of solar-system observations. In the field of orbit computation, the computational challenge ensuing from the exploding data flow has been one motivation for the active research in both theoretical and computational methods in the recent years. The huge observational databases resulting for solar-system objects will require efficient tools for the real-time analysis of the detections, in particular for automated identification of astrometric observations, and orbital analysis including dynamical classification and impact probability estimation. While the solution of the identification problem is a necessity in the data reduction pipeline of any large-scale survey, the end-results such as the vast orbital databases will enable more detailed studies of the small body populations.

In theoretical research, two styles of solutions to the inverse problem of orbit computation has been investigated, both focusing on the case where the observational data is not abundant (e.g., not sufficient for a least-square solution). On one hand, Milani *et al.* (2005a) have further refined their line-of-variations (LOV) techniques (Milani 1999). They have applied multiple solutions along the LOV for better mapping the orbital uncertainty to be used in applications such as identification or impact monitoring (Milani *et al.*, 2005b). For what they term "very short arcs", Milani *et al.* (2004) have taken a geometric approach to uncertainty estimation. They use a set of virtual asteroids to describe the uncertainty region by triangulation of the unknown range–range-rate plane.

On the other hand, based on the concept of statistical orbit computation (Muinonen and Bowell, 1993) Virtanen *et al.* (2003) further improved their Monte Carlo technique for exiguous data (Virtanen et al. 2001). They applied the automated statistical orbital ranging to the observed population of transneptunian objects (TNOs) at the time, showing its potential to large-scale automated analysis. In consequence, a web based service for TNO ephemeris prediction was implemented (TNOEPH†, Granvik *et al.* 2003). Muinonen *et al.* (2006) described a new Monte Carlo technique termed Volume-of-Variation (VoV), a fully-nonlinear six-dimensional generalization of the line-of-variation techniques. In degree of nonlinearity, the technique by Chesley (2005) falls between the LOV applications and VoV, sampling in a plane rather than along a line or in a 6D phase-space volume.

Some important breakthroughs have been experienced in the computationally demanding problem of identification for exiguous, e.g. single-night, data. Granvik and Muinonen

† http://asteroid.lowell.edu/cgi-bin/virtanen/tnoeph

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(2005) made use of statistical ranging in building an algorithm to search for possible linkages among large subsets of simulated asteroid observations. In Granvik *et al.* (2005), the identification algorithm was put to test with real data by successfully linking single-night VLT observations. Another approach to the problem was put forward in Milani *et al.* (2005c). Following the geometric approach in Milani et al. (2004), they are able to link together single-night observations simulated for the Pan-STARRS project.

An important feature of the new surveys is the improving astrometric accuracy due to advanced CCD technologies. This improvement will have a major impact on the accuracy of the derived orbital elements (Muinonen and Virtanen, 2002; Hestroffer and Berthier, 2005). Moreover, the entire orbit computation problem will be affected (e.g., Muinonen *et al.*, 2005): the astrometric implications of the finite size and irregular shapes of the asteroids need to be modeled, because for mas-accuracies (or below) the photocenter-barycentre offset becomes important (Kaasalainen *et al.* 2005). The full inverse problem in future surveys may thus encompass solving for the sizes, shapes, and masses as well as relativistic effects simultaneously for large numbers of asteroids.

4. Asteroid families and their ages (D. Vokrouhlický)

Asteroid families, defined as a collection of objects with similar proper semi-major axis, eccentricity and inclination, are believed to be produced by a collisional breakup or large cratering event on a precursor body. They are important to study (i) the mineralogical structure of the parent bodies by spectroscopy, (ii) the outcomes of disruption events over a size range inaccessible to laboratory experiments, (iii) the collisional history of the main belt, (iv) the sources of interplanetary dust and the efficiency of its accretion onto the planets and the Earth (see Nesvorný *et al.* (2005c) for a recent review).

Extracting this information from asteroid families, however, is not always straightforward. For example, many observed family members have had the spectroscopic properties affected by space weathering (e.g. Jedicke *et al.* 2004; Nesvorný *et al.* 2005). Some families reside in highly populated regions of the main belt, such that discriminating family members from interlopers can be difficult, even impossible (e.g. Migliorini *et al.* 1995). Family members undergo collisional evolution, thus the size frequency distribution of the population slowly evolves toward the same shape as the background population (e.g. Bottke *et al.* 2005a,b); then the dust production fades (e.g. Nesvorný *et al.* 2005b; Farley *et al.* 2005). Finally, the initial configuration in proper elements space, set by the ejection velocity from the parent body, undergoes modifications over time via gravitational and non-gravitational perturbations (e.g. Bottke *et al.* 2001, 2002; Nesvorný *et al.* 2002a; Dell'Oro *et al.* 2004; Carruba *et al.* 2005). Thus, older families evolve and gradually obscure their initial velocity field. The same effects can even erase the signatures of small families, making it difficult to use them as constraints in modeling the evolution of the main belt (e.g. Marzari *et al.* 1995, 1999; Bottke *et al.* 2005a). A common problem affecting all of these issues is the unknown value of a key parameter, the *age* of the families. Here we report on recent advances, in particular on the problem family chronology. We start by discussing the two most reliable methods available today.

Backward numerical integration.– The most straightforward approach is the numerical integration of family-members' orbits into the past. The goal is to show that in some previous epoch the orbits were nearly the same, meaning alignment of nodes (Ω) and perihelia (ϖ). Today these angular variables are random, but just after the family progenitor break-up, they must have been tightly clustered. Nesvorný *et al.* (2002b, 2003) used this method to determine the age of the Karin (5.8 ± 0.2 My) and Veritas (8.3 ± 0.5 My) families (finally setting the case of the latter whose young age was first postulated by

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Milani & Farinella, 1994), and also found that the tight family associated with (4652) Iannini is probably $\lesssim 5$ My old. Unfortunately this method cannot be used to determine ages of asteroid families older than ~ 10 My, because it is difficult to accurately track orbital evolution of asteroids over that long period of time.
Modeling of family spreading via thermal forces and torques.– The asteroid families are subject to slow spreading and dispersal via the Yarkovsky thermal effect (Farinella & Vokrouhlický 1999; Bottke *et al.* 2001, 2002). Thus, for old families the proper elements do not reflect the immediate outcomes of their forming events, but fill a significantly larger volume. Small asteroids often tend to reside at the extreme values of the proper semimajor axis and that was taken as a signature of thermal torque alignment of their spin axes with normal to the ecliptic, thus accelerating the migration rate by the Yarkovsky effect. Using this approach, Vokrouhlický et al. (2005a,b,c) determined the age of 6 asteroid families, Astrid and Agnia being the youngest (~ 100 My old) and Eos the oldest ($1.3^{+0.15}_{-0.2}$ Gy). The intrinsic accuracy of the age determined with this method is $\sim 10\%$ if the albedo value is accurately known, otherwise it degrades to $\sim 40\%$. Nesvorný & Bottke (2004) used the Yarkovsky effect on the angular variables (Ω and ϖ) to refine the age of the Karin cluster (5.75 ± 0.05 My) and infer some information of its members' spin axes and surface thermal properties. Carruba *et al.* (2005) proposed the dynamical link of several V-type asteroids to the Vesta family, suggesting its age must be $\gtrsim 1.2$ Gy.

Next we list 3 useful but less reliable methods to have a hint on the family ages:
Inferences from spin axes orientation.– This can only be done in special circumstances. E.g., Slivan (2002) found that many $20 < D < 40$ km Koronis family members have a unusual rotation state, the prograde rotators with obliquities between $42° - 50°$ and nearly identical spin periods ($7.5 - 9.5$ hours), the retrograde with obliquities between $154° - 169°$ and spin periods < 5 hours or > 13 hours. Vokrouhlický *et al.* (2003) showed these spin had been affected by spin-orbit resonances and thermal torques; this allowed to estimate that the Koronis family is ~ 2.5 Gy old.
Cratering records of family members.– Perhaps the oldest method to estimate family age is to count craters on surface(s) of its members (assuming these bodies have not experienced disruption events after the family formation). This has been accomplished for several family asteroids, including (951) Gaspra in the Flora family and (243) Ida in the Koronis family. (951) Gaspra is believed to have an age of $100 - 300$ My (consistent with Nesvorný *et al.*, 2002a). It is more difficult to estimate an age for (243) Ida, with craters close to empirical saturation, but the best estimates suggest it is over 2 Gy old. The problem is that this method depends on rare visits to asteroids by spacecraft.
Collisional dynamics studies.– The goal is to model the evolution of the size frequency distribution of the family members and compare it to the observations (e.g. Marzari *et al.* 1995, 1996, 1999). For example, Marzari *et al.* (1995) fit the size distribution of the Koronis and Themis families, determining for both an age exceeding ~ 2 Gy. There are, however, many caveats, including the unknown initial size distribution in each family, and the poorly known parameters governing the collisional evolution in the main belt.

5. Non gravitational perturbations on asteroids/comets (M. Brož)

The strongest non-gravitational perturbation acting on small asteroidals (in the size-range from 10 cm up to 10 km) is the Yarkovsky/YORP effect. The basic principle of this phenomenon is the absorption of solar radiation and its anisotropic thermal reemission. For recent reviews see Bottke *et al.* (2003) or Brož *et al.* (2005a).

A first detection of the Yarkovsky effect was reported by Chesley *et al.* (2003), who directly measured a non-gravitational semimajor-axis drift of the asteroid (6489) Golevka by a radar-ranging technique. The observed value of the acceleration fits very well with the calculated Yarkovsky acceleration, as predicted by Vokrouhlický *et al.* (2000). A dozen of similar opportunities for the detection of the Yarkovsky drift within the next decade were predicted by Vokrouhlický *et al.* (2005b) and Vokrouhlický *et al.* (2005c). When the shapes of asteroids are known or the asteroids are binary, they computed the Yarkovsky accelerations with a precise but time-consuming numerical method, solving the 1-dimensional heat diffusion equation, individually for all surface elements.

Concerning the rotational dynamics, Vokrouhlický & Čapek (2002) and Čapek & Vokrouhlický (2004) calculated YORP torques for a large set of artificial bodies, with shapes similar to real asteroids. This allowed to include the YORP-driven changes of rotational states into evolutionary models of asteroid families or unstable populations. The Yarkovsky/YORP effect serves as an mechanism explaining the existence of several observed unstable populations, which have to be continuously resupplied from some large reservoirs of asteroids. The asteroids located in the neighborhood of the 5/2 mean motion resonance with Jupiter were studied already by Vokrouhlický *et al.* (2001). They predicted the retrograde rotation of the asteroid (2953) Vysheslavia, which was indeed confirmed by photometric observations by **?**. A search for unstable asteroids in the surroundings of the 3/1 resonance was conducted by Guillens, Vieira Martins & Gomes (2002). Morbidelli & Vokrouhlický (2003) constructed a model of the Near-Earth asteroids being resupplied from the Main Belt. They assumed the Yarkovsky/YORP effect slowly pushes Main-Belt asteroids towards major mean motion resonances, which then quickly increase the orbital eccentricities and drive asteroids to the Near-Earth space. This scenario explains the observed number of NEA's and the difference between the observed slopes of absolute magnitude distributions of NEA's and MBA's, which corresponds almost exactly to the dependence of the Yarkovsky/YORP effect on size. In agreement with this model, La Spina *et al.* (2004) reported a preference of retrograde-rotating asteroids among the observed NEA's.

Tsiganis *et al.* (2003) studied the population of 22 bodies inside the 7/3 mean motion resonance with Jupiter. They proved that the Yarkovsky drift may keep it in steady state, as it pushes members of the neighboring Koronis and Eos families towards the resonance. An independent confirmation is the observed confinement of orbital inclinations between the resonant asteroids and the two families. Brož *et al.* (2005b) discussed 50 unstable asteroids located in the 2/1 resonance and interpreted them similarly as Main-Belt asteroids pushed by the Yarkovsky/YORP effect. Their conclusion is based on extensive comparisons of orbital evolutionary tracks, dynamical lifetimes and size distributions.

Cometary bodies are perturbed mainly by the Sun-driven sublimation of ices from the surface and the corresponding rocket effect. For a review see Yeomans *et al.* (2004). The older four-parameter Extended Standard Model was superseded by the Rotating Jet Model, which assumes one or more jets emanating from a rotating nucleus; it can also account for orbit-to-orbit and seasonal changes of the outgassing activity. Chesley & Yeomans (2005) applied the latter model to selected space mission targets. In some cases, it seems to be possible to deduce the physical parameters (i.e., the orientation of the spin axis and the positions of the jets) from astrometric data alone. On the other hand, models like Davidsson & Gutiérrez (2005) try to combine the non-gravitational changes of orbital elements with the nucleus rotational lightcurve and the water production rate.

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