Current Questions in Cometary Dynamics

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We summarize the most important findings reported, and unanswered questions identified, in the review chapters on cometary dynamics in this book. Comments are also offered on the significance of these problems — and thus of cometary dynamics — for making progress on several major issues of solar system cosmogony.

1. INTRODUCTION

Cometary dynamics involves the study of transfer processes between widely separated regions of the solar system. Essentially, it aims to understand how cometary orbits change so that comets are brought between outer and inner ranges of heliocentric distance (r). These provide, respectively, cold storage of the cometary volatiles for billions of years, and then the possibility to exhibit cometary activity while consuming those volatiles. One thus talks of distant reservoirs that are still active today, supplying new comets for their first entries into orbits plunging into the water sublimation zone (this has classically been considered as $r \leq 2.5–3$ AU, but under some circumstances H_2O may sublimate at significantly larger distances, and modern observational techniques have allowed the discovery of many comets with perihelia around 5–10 AU).

Of course, our interest in cometary dynamics extends well beyond the currently operating mechanisms for bringing comets into "observable" orbits (i.e., orbits with small enough perihelion distance). It also incorporates the past evolution, and even formation, of the distant reservoirs. Thus the scope is ambitious enough to involve an attempt to link the orbital statistics of observed comets to critical features of solar system cosmogony such as the origin of the giant planets and the transneptunian disk. Even though such studies are by necessity limited to statistical properties of the transfer processes, there is also the intriguing challenge of understanding the places of certain particular comets within the resulting scenarios. Examples are the comets for which D/H ratios and a range of molecular abundances have been observed (1P/Halley, 1995 O1 Hale-Bopp, 1996 B2 Hyakutake), and the target comet of ESA's *Rosetta* mission (67P/Churyumov-Gerasimenko).

Most of the progress of research in these areas, reported in the chapters of this book, is of relatively recent origin. In particular, it has important connections to the discovery and characterization of the Edgeworth-Kuiper belt during the last decade. But this book also describes much progress in the classical area of cometary dynamics that seeks to explain the fine details of observed cometary motions and link as many apparitions of periodic comets as possible, while accurately representing all observations. There is thus a trend toward better astrometric accuracy and improved coverage of the orbits. Moreover, this is getting used along with data on gas production rates and outflow kinematics to construct realistic models of the jet force, from which physical properties of the nuclei like their masses may be deduced.

We realize the important interconnection between cometary physics and dynamics. It is not possible to fully understand the thermophysical or chemical characteristics of a cometary nucleus without reference to its orbital history and formation region, and the details of the orbital motions provide a promising tool to probe structural and evolutionary properties of cometary nuclei — primarily density or porosity and dust coverage. In fact, cometary motions are affected by nongravitational forces that obviously depend on the physical properties of the nuclei, showing that cometary dynamics is influenced by physical properties as well. Moreover, the fate of an individual comet arriving from the Oort cloud may take entirely different courses, depending on the details of the nongravitational effects. Finally, dynamical models for the transfer of comets into "observable" orbits have to be judged against the distribution of observed comets, and this involves a judgement of both observational biases and physical evolutionary effects. Hence cometary dynamics cannot be understood without reference to cometary physics.

The rest of this paper will focus on some of the most interesting aspects of cometary dynamics, attempting to highlight a number of unresolved problems and identify needs for continued research in the future. For references to published literature the reader should primarily consult the full review papers in this book, since in many cases the relevant papers will not be cited here.

2. ORIGIN OF COMETARY POPULATIONS

2.1. Infeed and Capture

It is now considered a well-established fact that the Jupiter family (i.e., short-period comets with Tisserand parameters T in the range $2 < T < 3$) predominantly originates in multiplanet captures from the transneptunian population (see *Jewitt,* 2004; *Duncan et al.,* 2004). By contrast, the contribution from the Oort cloud, while not nil, should be rather small. Currently the most interesting question seems to concern the relative contributions of two possible source populations: the "classical Kuiper belt" or the "scattered disk" (*Duncan et al.,* 2004).

The classical Kuiper belt is a population of objects that formed well outside Neptune's orbit and stayed there for the age of the solar system; this population has undergone strong collisional evolution. The present infeed of such objects into Neptune-crossing orbits is due to resonant interactions with the giant planets that increase the eccentricities over a very long timescale, and those interactions should affect only a fraction of the entire population.

On the other hand, the scattered disk consists of objects that started out from encounters with Neptune and subsequently reached a temporary asylum by resonant decrease of eccentricity (and thus increase of perihelion distance). In this case, the present infeed is to be seen as the inevitable return of the refugees, and essentially the whole population will eventually be affected, even though at present only a part of it is likely to be concerned.

Estimates based on the number of discoveries of objects with diameters $D \gtrsim 100$ km indicate that the two populations are about equally numerous. If this holds true down to $D \lesssim 10$ km, their relative contributions to both the Centaurs and the Jupiter family should be in inverse proportion to the typical timescales of their respective infeed mechanisms. The argument of *Duncan et al.* (2004) is that the infeed timescale is much shorter for the scattered disk, which is hence the dominating source of the Centaurs and the Jupiter family.

This conclusion needs to be further scrutinized, as more observations will yield improved estimates of population sizes for both the Jupiter family, the Centaurs, the Kuiper belt, and the scattered disk. In particular, the extrapolation of numbers of objects from $D \gtrsim 100$ km to $D \lesssim 10$ km is risky, especially if collisionally evolved and unevolved populations are compared. At present, the estimated number (~100) of $D > 100$ km Centaurs appears on the small side compared with the infeed rates expected from the two transneptunian reservoirs (10^{-5}–10^{-4} yr^{-1} for a population of ~10^4 $D >$ 100 km objects and infeed timescales of 10^8–10^9 yr), given a Centaur dynamical lifetime of ~10^7 yr.

However, on the one hand, better knowledge of the population sizes may in fact remove any trace of a discrepancy, and on the other hand, it also seems necessary to spend further effort on constraining the dynamical timescales. For instance, if large fractions of the Kuiper belt and scattered disk populations are immune to infeed toward Neptune over much longer timescales, it is not even certain that the two sources are rich enough to explain the Centaurs — or, indeed, the Jupiter-family comets.

Whether or not the current conclusion in favor of the scattered disk as the principal source holds up against such efforts, the final answer is bound to have great cosmogonic significance. This is because the scattered disk, presumably, is not collisionally evolved to the same degree as the classical Kuiper belt — otherwise it would be hard to explain the current population size. Hence, while Jupiter-family comets derived from the Kuiper belt would be collisional fragments (*Farinella and Davis,* 1996), those coming from the scattered disk may still be collisionally unevolved. As a consequence, the findings of the *Rosetta* mission will have to be viewed in a framework that is quite different, depending on which is the actual source population.

Of course, it is of great importance to establish what chemical effects the collisional evolution would have. To what degree is the structure and composition of cometary ice different, comparing a primordial nucleus with one that is a collisional fragment? Studies of differentiation effects in large transneptunian objects (*Choi et al.,* 2002) shed some light on this, but more work is needed.

There is also a third source, however, as already mentioned. The Oort cloud, and especially its inner core (with semimajor axes a in the approximate range $5000 < a <$ 20,000 AU), is certainly contributing some — as yet unknown — fraction of the Jupiter-family comets as well as the Centaurs. Its contribution to the Halley-type comets (orbital periods $P < 200$ yr and $T < 2$) is undisputed, but the apparent preference for low-inclination orbits of Halley-type comets is a problem, if the classical Oort cloud with its isotropic orbital distribution is considered as the main source. Thus a flattened inner Oort cloud has also been suggested as the principal source of Halley-type comets (*Levison et al.,* 2001), but a full treatment of the infeed and capture from the inner Oort cloud remains to be made.

2.2. Origin of Source Populations

Considerable progress has been made in the modeling of planetesimal scattering from the accretion zone of the giant planets, and hence some insights into the formation of the Oort cloud, Kuiper belt, and scattered disk have also been reached (see *Morbidelli and Brown,* 2004; *Dones et al.,* 2004). Based on the most realistic simulations available so far, it seems that the inner and classical parts of the Oort cloud should be about equal in mass and number of comets, and that the inner Oort cloud should be only slightly "flattened," i.e., show only a slight preference for prograde over retrograde orbits (*Dones et al.,* 2004). However, effects that are likely significant have been neglected, so the picture is not yet complete.

Thus a comprehensive study of Oort cloud formation in combination with giant planet accretion, and with the young solar system placed in a dense environment of surrounding stars, remains to be performed. In parallel, understanding the origin of the Kuiper belt and scattered disk is also presenting a growing challenge. Recent discoveries or suggestions of a mixed Kuiper belt structure involving dynamically hot and cold components with different size and color distributions, with an outer edge at a ~ 50 AU, are prompting investigations of more complex formation scenarios than used by the early models (*Morbidelli and Brown,* 2004).

There may still be a long way to go, and some of the observational data — e.g., on size distributions and frequency of occurrence of binaries — may need to be extended. But the outcome in terms of a more solid picture of how the transneptunian structures formed along with the giant planets is eagerly awaited, to say the least!

3. NONGRAVITATIONAL EFFECTS

Among recent progress in the treatment of nongravitational effects, let us first mention the self-consistent treatment of such effects when calculating both the osculating orbit near perihelion and the original orbit before entry into the planetary system (see *Yeomans et al.,* 2004). It has been found that the original reciprocal semimajor axes $(1/a)_{orig}$ thus derived may differ quite significantly from the corresponding quantities derived assuming purely gravitational motion, and thus the negative reciprocals found for a small set of long-period comets may be mostly explained away by this effect (*Królikowska,* 2001). Important as that may be, it is equally important to realize that the comets with positive $(1/a)_{orig}$ are subject to nongravitational forces as well. Neglecting this, one may significantly affect the width of the Oort peak (*Królikowska,* 2001) and the apparent "inner edge" of the infeed of new comets. Hence, the apparent discrepancy between the inner edge at $a \simeq 20{,}000$ AU and the theoretically expected one at 28,000 AU (*Levison et al.,* 2001) may not be real, or the problem may be aggravated — further research is necessary.

A related problem, also of importance, is what influence the nongravitational effects may have on the capture of Oort cloud comets into short-period, Halley-type orbits. This concerns comets with small perihelion distances q — typically, $q \leq 2.5$ AU. From the fact that the typical, indirect jovian perturbation of 1/a for such a comet (*Rickman et al.,* 2001) is much larger than the typical nongravitational perturbation, one would expect the latter to contribute very little. But there is an important difference between the random-walk nature of the jovian perturbations and the systematic progression of the nongravitational effect. Imagine that at least half the comets experience a decrease of the semimajor axis — for instance, due to an excess of outgassing on the preperihelion branch of the orbit. In the absence of a nongravitational effect the comets start their random walk in 1/a dangerously close to the parabolic limit, and it is a well-known fact that this is a severely limiting factor for the capture efficiency (*Everhart,* 1972). Even a slight tendency to walk away from this ejection limit might then have an important consequence by delaying the ejections and thus increasing the chances for a decisive capture event by direct gravitational interaction with Jupiter.

This possibility remains to be investigated. Let us only add that, should it be the case that nongravitational effects may indeed influence the capture of Oort cloud comets significantly, there will also be a dependence on physical properties. For instance, comets with small nuclei will be preferentially affected.

The progress that has been achieved in detailed characterization of the nongravitational effects is likely to continue in the future. However, real breakthroughs may require the advent of new telescopes and instrumentation. When 30–100-m telescopes come on line, imaging of the innermost coma regions should, by resolving the dust jet structures, allow the measurement of much more accurate positions of the nuclei than previously possible. Likewise, this will yield additional information on the main direction of outflow, thus further helping to constrain the nongravitational force models.

When it comes to estimating nuclear masses, a main reason for optimism is the prospect of measuring the nongravitational precession of the perihelia with considerable accuracy (see *Davidsson and Gutiérrez,* 2003). In the framework of the standard model these are expressed by the parameter A_1. This parameter has a significant advantage over A_2 (which similarly measures the delay of perihelion passage) in that the effect, to first order, does not depend on the perihelion asymmetry of the gas production curve but only on the total amount of gas produced from the nucleus. Hence, facing uncertainties over the actual amount of this perihelion asymmetry, it is easier to interpret the A_1 effect than the A_2 effect.

4. CONCLUSIONS

As in the past, cometary dynamics continues to tackle problems of fundamental significance for understanding the formation and evolution of the solar system. We have highlighted several examples of further progress to be expected, as both numerical simulations and observations continue to improve. This will involve sharpening our picture of how the giant planets formed and the transneptunian disk and Oort cloud were shaped. It will also allow a better understanding of how comets formed and evolved into their present orbits, and — hopefully — a more solid framework for interpreting the host of physical and chemical data already obtained and likely forthcoming with *Rosetta* and other space missions.

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Rickman: Current Questions in Cometary Dynamics. 207. of occurrence of binaries â€" may need to be extended.Â As in the past, cometary dynamics continues to tackle problems of fundamental significance for understanding the formation and evolution of the solar system. We have high-lighted several examples of further progress to be expected, as both numerical simulations and observations continue to improve. This will involve sharpening our picture of how the giant planets formed and the transneptunian disk and Oort cloud were shaped. Comet, a small body orbiting the Sun with a substantial fraction of its composition made up of volatile ices. Comets are among the most-spectacular objects in the sky, with their bright glowing comae and their long tails. Comets can appear at random from any direction as they move in eccentric orbits around the Sun.Â While every effort has been made to follow citation style rules, there may be some discrepancies. Please refer to the appropriate style manual or other sources if you have any questions. Select Citation Style. MLA APA Chicago Manual of Style. MOND, Non-gravitational forces, Cometary dynamics. 1. 2 3 3 5 7 9 11 11. 2 lucie MAQUET1 and frÃ©dÃ©ric PIERRET2.Â This model is used to generate cometary ephemeris and gives a good estimate of the non-gravitationnal eect for cometary orbits. These non-gravitationnal forces are obtained by tting the astrometrical data but it is important to take into account all of the small eects, such as relativistic terms, to estimate correctly the outgassing (see [10]). That is why the.Â With the precision of current observations, it is completely negligible. Table 2. Truncated values of the orbital elements and non-gravitational pa-rameters of the comets from the JPL small bodies browser. For the computa-tions, we used non-truncated values available on the JPL website.