DYNAMICS OF DISCS AND PLANETS
12 August to 18 December 2009

Report from the Organisers:
A Morbidelli (Nice), RP Nelson (Queen Mary, London), GI Ogilvie (Cambridge), JM Stone (Princeton), MC Wyatt (Cambridge)

Scientific background

Ever since the discovery in 1995 of an object with half the mass of Jupiter in a four-day orbit around the star 51 Peg, it has been clear that the dynamics of extrasolar planetary systems can be quite different from that of our Solar System. More than 400 extrasolar planets have now been found, including at least 40 systems with multiple planets, some in resonant configurations. Their diversity must originate in the properties of the protoplanetary disc of dusty gas out of which they form, the dynamics of the formation of the planetary core, and the subsequent interaction of the planet with the surrounding disc, with other planets, and with the central star.

Over the past decade, there has been significant progress on theoretical aspects of the planet formation process. Two viable models of planet formation have been explored, core accretion (growth of dust into planets through mutual collisions) and gravitational instability in the disc, and several modes of angular momentum exchange between planet and disc have been identified which may explain the proximity of the 51 Peg planet to its star. However, many of the stages of planet formation remain poorly understood. In part this is because of a lack of knowledge of the physical nature of protoplanetary discs, although this has increased dramatically in recent years owing both to observations of such discs and to computational modelling of their (magneto-) hydrodynamics. The outcome of planet formation is also becoming more tightly constrained, through the rapidly growing number of systems known to have either extrasolar planets or planetesimal belts analogous to the asteroid and Kuiper belts. The discovery of planetesimals and dwarf planets in the Kuiper belt beyond Neptune is also leading to a revision in our understanding of the formation and evolution of the outer Solar System. The wide array of phenomena seen in all systems is providing a valuable opportunity to enhance our theoretical understanding of the processes at play, and new areas of celestial mechanics and disc dynamics are being opened up as a consequence.

At this time of unprecedentedly rapid progress, the aim of this programme was to consolidate and advance our theoretical understanding of how extrasolar planetary systems form and evolve, by bringing together world-leading researchers in disciplines ranging from accretion disc theory, planet formation, planet-disc interaction and Solar System dynamics.

Structure of the Programme

The scientific programme was divided into three broad themes, organised both by the mathematical and physical approaches needed to study them, and by the chronological order in which they operate in the process of planetary system formation and evolution: (1) dynamics of gaseous accretion discs; (2) dynamics of planetesimals and planets embedded in gaseous discs; (3) celestial mechanics of planet and planetesimal interactions. Equal weight was attached to each theme, and this was reflected in the ~ 100 participants whose expertise spanned the complete range of analytical and numerical techniques employed in this field. In practice the themes overlap to some extent, with many participants having interests in two or more themes, and interactions between the themes was considered to be important to making progress. Thus, while we encouraged the programme to tackle these themes in the order above, by arranging workshops around these topics at the nominal start of each theme, and by suggesting that participants select dates of attendance accordingly, this was not rigidly adhered to. This allowed the agenda outside the workshops to be set by the interactions that developed amongst participants, resulting in a mix of focussed discussions and cross-fertilisation of ideas that proved to be very productive.

Throughout the programme we organised a schedule of seminars and discussions, typically twice a week when the workshops were not in progress. These were led usually by participants of the DDP programme, and occasionally by researchers from nearby institutions. While some preferred the conventional style of a formal seminar, we encouraged as much discussion as possible and several speakers agreed to give informal blackboard presentations, which are unusual in this subject area. One of these was even given by a participant of the concurrent NAG programme, who had formerly worked in Hamiltonian dynamics and could relate to the N-body dynamics of planetary systems. We also had stimulating round-table discussions on planetary migration and the excitation of eccentricity. On a daily basis, we occupied the mezzanine area of the Institute for lengthy coffee "breaks", which in fact provided the focus for much of the scientific discussions.

Workshops

The Dynamics of Discs and Planets

17-21 August 2009
Organisers: RP Nelson, GI Ogilvie

A large international conference was held during the second week, the aim of which was to review the current state of research in the science areas covered by the programme, and define key outstanding problems that might be the focus of collaborative research during the next 4 months. The consensus of opinion seems to be that the conference was very successful in meeting both of these goals.

To achieve these aims, the conference programme included ten longer invited review talks, presented by recognised world-leaders in research, which set the broader context for each conference session and provided background material useful for PhD students and early-stage researchers. A total of 30 shorter talks were also presented, describing the results of the most recent research, and 80 posters were displayed (and presented in 1 minute poster-talks). The programme was organised into 8 sessions, each of which including 30 minutes discussion, on topics of: Observations of Protoplanetary Discs; Protoplanetary Disc Modelling; Dust Coagulation and Planetesimal Formation; Formation of Terrestrial, Super-Earth and Giant Planets; Disc-planet Interactions and Migration; Stability and Long-term Evolution of Planetary Systems; Observations of Extrasolar Planets; Debris-Discs: Observations and Theory.

The broad nature of the conference makes it impossible to summarise the full range of discussions which took place, but overall the atmosphere was very lively and interactive. Discussion highlights include: the clearing mechanisms responsible for the so-called transition discs which are now being observed in abundance; the role and nature of dead-zones in turbulent protoplanetary discs; planetesimal formation via the streaming instability in turbulent and laminar discs; the evolution of self-gravitating discs and the role of gravitational collapse in forming giant planets; the role of disc thermodynamics in determining the rate and direction of planetary migration; the formation of the giant planet cores via oligarchic growth in the presence of planetary migration; planetary scattering as a means of forming eccentric planetary systems (and long-period planets); implication of debris disc observations for models of planetary formation.

Planetesimal Formation

28-30 September 2009
Organisers: A Morbidelli, JM Stone

The second workshop focussed on a fundamental and open issue of planet formation: the accretion of the first planetesimals. It was intended to be fairly technical. There were 13 invited talks of one hour each and four contributed talks of half an hour. An hour-long discussion concluded each day.

About a third of the lectures were devoted to discuss the properties of the proto-planetary disc in which planetesimals should have formed: is the disc gravitationally unstable? Is it turbulent? Are there zones with no turbulence? How well are we able to simulate the turbulence, given limitations in computing time and resolution? Is the disc in a quasi-steady-state or does it evolve violently? Quite of a consensus developed that magneto-rotational instability (MRI) is probably the driving mechanism of turbulence, even in the case of a magnetic field of null net-flux. A large "dead zone", where MRI does not drive turbulence directly, should exist in the central part of the disc near the mid-plane, but various stresses should propagate through this zone, so that gas density fluctuations and viscous transport should be operational there, nevertheless.

Some lectures were devoted to observational constraints from observations of proto-planetary discs, from analysis of the constituents of meteorites and the chronology of their formation and from the current size distribution of main belt asteroids. Laboratory experiments concerning the collisional coagulation/break-up of solid particles, and how that depends on sizes, collision speeds and internal structures, were also discussed, highlighting a "bouncing barrier" at about 1mm in size, for which particles tend to rebound rather than coagulate.

Five lectures discussed the mechanisms that have been envisioned theoretically for the rapid formation of planetesimals. It is now quite clear that the model of ordered growth, in which planetesimals form through collisional coagulation of pairs of smaller particles, meets fundamental difficulties. Instead, the favoured mechanism now contemplates the formation of high-density localised clumps of small particles, whose evolution is then dominated by self-gravity. The size of the particles involved in this clumping-process and the mechanism of concentration have been major subjects of debate. Metre-size particles are very effectively clumped by spiral density waves or turbulent-induced fluctuations in the gas distribution, as well as by the recently-discovered "streaming instability", which is due to the perturbations that random particle concentrations exert on the gas. A big question, though, is how these metre-size boulders could have formed in first place. Moreover, the fundamental constituents of meteorites, chondrules and CAIs, are much smaller than one metre. A model was presented according to which chondrule-size particles are concentrated in the low-vorticity regions of the disc. Self-gravitating clumps of chondrules, though, should take a long time to contract into planetesimals, so that the survival of these clumps is questionable. Thus, no definitive conclusion was reached at the workshop, but the coherent presentation of the various mechanisms and constraints, as well as the frank confrontation among the major experts in the field, will likely trigger further fundamental progress in the near future.

Dynamics of Outer Planetary Systems
Satellite Meeting at the Royal Observatory, Edinburgh
9-11 November 2009
Organisers: WKM Rice, MC Wyatt

Observational detection biases mean that the majority of the 400 known extrasolar planets are close to their stars ($\ll$ 10AU). This 3-day workshop focussed on the dynamics and physical processes that affect the less well-studied outer regions ($\gg$ 10AU) of planetary systems. The planetesimal populations of these regions are seen as debris discs which also provide indirect evidence for the formation of planet-sized objects, but it is only recently that extrasolar planets were detected there: this workshop took place 1 year after the first such planets were discovered through direct imaging. The workshop programme was divided into 6 sessions on themes of observations, Solar System, planetesimal growth, planetestimal evolution, origin of outer planets and interactions with outer planets. Each session comprised 2 review talks and 3-4 contributed talks, as well as discussion time, and the workshop was attended by 66 participants.

There was much discussion on the origin of the newly discovered planets, which present significant challenges to formation by core accretion. Thus there was renewed interest in the gravitational instability mechanism, which is less favoured as the explanation of close-in planets, but was shown to be consistent here albeit subject to constraints on protoplanetary disc properties. The possibility that outer planets form closer in but then migrate out was discussed, and considered to be viable both through scattering of planetesimals or amongst planets in a dynamically unstable system, though the outcome is sensitive to initial conditions. The Solar System constraints are very relevant, and progress was presented addressing challenges to the leading "Nice" model, which envisages an initially compact Solar System that expanded following a dynamical instability. It was recognised that external influences can be important, both for planets and planetesimals, particularly in a stellar cluster where interaction with the gravity and radiation of nearby stars can have high probability. Stochastic processes were also discussed for debris discs, and whether anomalous systems like Vega require recent collisions (as previously thought), or can be explained by steady state processes (the new interpretation). Another outstanding issue was the origin of debris disc stirring, for which models invoking growth of Pluto-sized objects or secular perturbations of giant close-in planets were presented, along with the possibility that the discs are in fact not stirred, with collisions occurring at low velocity like in planetary rings. Although the competing physical and dynamical processes operating in these regions are only just beginning to be explored, the discussions at the workshop will be sure to strengthen our understanding of this frontier of extrasolar planetary science.

Programme Summary
15 December 2009
Organisers: A Morbidelli, RP Nelson, GI Ogilvie, JM Stone, MC Wyatt

This one day workshop was designed to enable participants to summarise new projects or insights enabled by the programme. It consisted of 12 short (20 minute) presentations, followed by an overall summary by programme organiser A. Morbidelli. Presentations were organised into three sessions on (1) gas dynamics in protoplanetary discs, including the effects of self-gravity and realistic thermodynamics, (2) planet-disc interaction and migration, and (3) the N-body dynamics and stabilty of planetesimals and planetary systems.

The Programme Summary identified several important themes and directions for future research in the field. These included continued investigations of: (1) The internal structure of gaseous discs. For example, does the presence of a "dead-zone" at the disc midplane affect the overall evolution and accretion rate in the disc, and can observations detect or rule out the presence of a dead zone? (2) Collective effects in the formation of planetesimals. For example gravitational instability triggered by dense clumps of solid particles formed through the streaming instability. (3) Type I migration in more realistic disc models including an accurate treatment of the thermodynamics. (4) The dynamical process of core formation for the giant planets, and the mechanisms by which giant planets can continue to accrete once they open a gap in the disc. (5) The relative roles played by migration and scattering of planets in planetary systems in determining the observed radial and eccentricity distributions of exoplanets. (6) The mechanisms responsible for forming the terrestrial planets.

The programme ended on a high note, with much optimism and renewed vigour amongst the participants to tackle these and many other issues discussed.

Outcome and Achievements

Many participants reported positively on their stay at the DDP programme. Almost everyone found the INI to be an environment conducive to discussion, collaboration and also private study. Many found the programme useful for meeting leading researchers known previously only through their publications, for renewing collaborations, and for generating new ideas. Having experts on hand and being able to talk to colleagues face to face were seen as very important. In several cases partipication in DDP led to further invitations and contacts. The programme also connected strongly with the Institute of Astronomy (IoA) and the Astrophysics group in DAMTP next door. For example, many participants were involved in a 2-day meeting from 6-7 September on *Angular Momentum Transport and Energy Release in Accretion Discs* held at the IoA in honour of the 60th birthday of one of the DDP participants J. Pringle.

It is inevitable that we can mention here only a few highlights of the diverse research carried out during the programme. Progress on numerous topics was reported by participants, including: role of viscosity and resistivity in turbulence driven by the magnetorotational instability in discs; corrugation modes in magnetically dead zones of protoplanetary discs; dynamics of corotation resonances; disc-driven winds; fragmentation of irradiated protostellar discs; saturation of the streaming instability in uniform and stratified disc models; orbital evolution of planetesimals embedded in turbulent discs; planetary accretion in binary stars; formation of giant planet cores; role of gap formation by a system of giant planets as an explanation for inner holes in transition discs; planetesimal driven migration; role of inertial waves in tidal interactions between planets and stars; viscous overstability in planetary rings; role of collisional damping in collisional cascades; steady state planetesimal size distribution with radiation forces; dust signatures of terrestrial planet formation; collisional evolution of extreme eccentricity planetesimal populations; formation of the outer Oort Cloud.

The programme facilitated dynamic interactions amongst participants that sparked numerous informal collaborations the impact of which will be felt for many years to come. For example a collaboration emerged involving M. Duncan, H. Levison and R. Nelson, thereby combining the N-body and hydrodynamic aspects of planet formation, to study the interaction with the gas disc of a planetary embryo that is migrating because of planetesimal scattering. Also, the basis was set for a new paradigm model of terrestrial planet formation that can explain the small mass of planet Mars through a new collaboration between A. Morbidelli and S. Raymond.

Many new theoretical results were presented during the programme generating new points for discussion. For example, a seminar by S. Ida on a mechanism of halting inward migration at the inner edge of a magnetically truncated disc stimulated investigations by several participants.

Everyone benefitted from having a wide variety of experts on hand, some perhaps outwith the normal realm of interaction for the field. For example, J. Burns brought an interesting perspective to the programme, through his expert knowledge of Saturn's rings and observations by the Cassini spacecraft, which bear a close relation to phenomena in protoplanetary discs. Discussions between A. Quillen and P. Lochak of the concurrent NAG programme led to progress on instability timescales in N-body systems.

The timing of the programme coincided with several important observational results, which allowed participants to focus on the analysis and interpretation of the most up-to-date data. For example, during the programme the first observations were taken for surveys by the Herschel space observatory that will test models for the structure and evolution of debris discs, and which many participants were involved in. Similarly fortuitous timing with respect to the CoRoT exoplanet transit survey resulted in a new collaboration between J.-L. Zhou, S. Ferraz-Mello and N. Haghighipour to consider the origin of the two super-Earth system CoRoT-7.

For some participants, the programme allowed fundamental improvements to numerical modelling techniques that will lay the foundation for many future discoveries. For example, the Athena code used for the study of the non-ideal magnetohydrodynamics of dusty protoplanetary discs was extended by J. Stone to include a fully parallelised static nested mesh as well as incorporating algorithms for the integration of dust particles with drag and feedback. Such techniques will allow the wide range of length scales in layered disc models, with regions of high resolution at the disc midplane or surface layers, to be followed.

Several participants were able to complete or make significant progress with major publications, including review articles by F. Adams (birth environment of the solar system) and W. Ward (planetary migration) and a book by N. Haghighipour (planets in binaries).