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PRIZE OF THE BEST THESIS 2015: STUDY OF DEBRIS DISCS THROUGH STATE-OF-THE-ART NUMERICAL MODELLING

Q. Kral[1] and P. Thébault[2]

Abstract. This proceeding summarises the thesis entitled "Study of debris discs with a new generation numerical model" by Quentin Kral, for which he obtained the prize of the best thesis in 2015.

The thesis brought major contributions to the field of debris disc modelling. The main achievement is to have created, almost ex-nihilo, the first truly self-consistent numerical model able to simultaneously follow the coupled collisional and dynamical evolutions of debris discs. Such a code has been thought as being the "Holy Grail" of disc modellers for the past decade, and while several codes with partial dynamics/collisions coupling have been presented, the code developed in this thesis, called "LIDT-DD" is the first to achieve a full coupling. The LIDT-DD model, which is the first of a new-generation of fully self-consistent debris disc models is able to handle both planetesimals and dust and create new fragments after each collision. The main idea of LIDT-DD development was to merge into one code two approaches that were so far used separately in disc modelling, that is, an N-body algorithm to investigate the dynamics, and a statistical scheme to explore the collisional evolution. This complex scheme is not straightforward to develop as there are major difficulties to overcome: 1) collisions in debris discs are highly destructive and produce clouds of small fragments after each single impact, 2) the smallest (and most numerous) of these fragments have a strongly size-dependent dynamics because of the radiation pressure, and 3) the dust usually observed in discs is precisely these smallest grains. These extreme constraints had so far prevented all previous attempts at developing self-consistent disc models to succeed.

The thesis contains many examples of the use of LIDT-DD that are not yet published but the case of the collision between two asteroid-like bodies is studied in detail. In particular, LIDT-DD is able to predict the different stages that should be observed after such massive collisions that happen mainly in the latest stages of planetary formation. Some giant impact signatures and observability predictions for VLT/SPHERE and JWST/MIRI are given. JWST should be able to detect many of such impacts and would enable to see on-going planetary formation in dozens of planetary systems.

Keywords: planetary system - debris discs - massive collisions - circumstellar matter

1 Introduction

Exoplanet science and more generally the study of extrasolar systems is the fast-growing part of astronomy today. Thanks to the recent spacecrafts Kepler and Corot, as well as ground-based observations from very large telescopes, our knowledge of exoplanets has grown enormously. Exoplanet masses, radii, orbits, atmosphere compositions can be probed using different techniques. Thus, each planetary system observed has its special characteristics that can be compared to our own: the Solar System. Understanding these planetary systems, their formation, their evolution, and searching for hidden components (e.g. planets) that are not bright enough to be observed directly was the main motivations of this thesis.

In extrasolar systems, not only are exoplanets found, but also rocky belts (such as the Kuiper belt in our own Solar System), comets, dust clumps, and gas. All of these with exoplanets, represent what we call a debris disc. Debris discs are found around about one fourth of stars and provide a way to explore the evolution of planetary systems. They also give clues about hidden components in the systems, as will be seen later. As part of the PhD work presented here, a new original approach has been developed to model dust in debris discs, which

[1] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
[2] LESIA-Observatoire de Paris, UPMC Univ. Paris 06, Univ. Paris-Diderot, 92195 Meudon, France

promises to revolutionise our understanding of these objects and extend our knowledge of planetary systems in general.

The study of debris discs is developing rapidly with the increasing quality of spatial and ground-based instruments and the possibility to observe detailed images of such discs. In the recent years, many observations with the space telescopes Hubble and Herschel, as well as the ground-based interferometer ALMA, or new instruments such as SPHERE or GPI, le(a)d to the discovery of structures within discs such as warps, brightness asymmetries, dust clumps, gaps, spiral features, spatial offsets that clearly show that complex physical interactions have to be accounted for when dealing with debris discs. One of the main explanations for the existence of these features is the presence of an exoplanet in the observed extrasolar system. This is how the famous β Pic b planet was first hypothesised indirectly a long time before its actual direct imaging in 2009 (Lagrange et al. 2009). This inclined planet forces the dust in the disc to gain some inclination and creates an observable warp from which we can indirectly infer the presence of a planet.

As well as being an indirect tracer for exoplanets, debris discs can be considered as potential leftovers from the planetary system formation, which tells us about formation of extrasolar systems. Moreover, debris discs are often the most easy component to detect in a planetary system due to their large cumulated dust cross section. Young stars with debris discs can be considered as ideal experimental labs to test planetary formation theories and discover hidden components, but one needs very complex models to handle all the different processes at play. Another area of research that has opened recently deals with "hot" debris discs also called exozodiacal dust (Lebreton et al. 2013). This hot dust close to their host stars should be short-lived, which is not compatible with its high observation rate (about 30% of stars contains hot dust, Absil et al. 2013). Complex interactions need to be modelled to find an explanation to this supposedly common process.

The main research interest of this thesis consists in modelling such discs and their interactions, mainly by developing complex numerical models that aim to make global simulations of such systems. In particular, the thesis was dedicated to develop the first self-consistent model able to couple both dynamical and collisional evolution of grains and planetesimals in such discs.

2 PhD thesis work

The work developed in this thesis mainly consisted in developing new numerical tools to understand debris discs and using them on the data that are already collected. The work can be divided into three parts that are all complimentary to one another. The first part was dedicated to help developing a partial coupling model of debris discs in order to understand the different mechanisms at play, and the limitations that should be overcome to create a full coupling. The heart of the thesis was to develop a powerful code that realises this full coupling and model debris discs in a self-consistent manner by including their interactions with their environments. Then, we started to use this model to learn more about planetary systems and in particular the late stages of planetary formation, which happen to be very chaotic and collisional.

A handful of numerical codes have been developed over the past few years to model debris discs physics, but no one fully succeeded to realise the ambitious goal described above. Motivated by this goal, we investigated the different ways to develop a new generation model able to self-consistently model debris discs, including the two crucial aspects of dynamics and collisions.

As a first test, our team developed a new model called DyCoSS (Thebault et al. 2012). This new algorithm was one of the most sophisticated at time of publication and implements a partial coupling to collisions. It is specifically designed to estimate how collisional lifetimes of grains are affected by dynamical perturbations, and how this variety of collisional lifetimes in turn affects the development of dynamical structures (resonances, PR-drag migrations, etc.). The code allows studying very fine spatial structures and has been used to study debris discs in binaries (Thebault 2012) or discs with an embedded or exterior planet (Thebault et al. 2012, 2014; Lagrange et al. 2012). Fig. 1 shows the structures created by a planet located in a broad disc at steady state. Resonant structures can be observed as well as a density gap at the planet position. This density gap should be empty as this is an unstable zone for the grains, but the constant production of small grains in the inner disc that are pushed on eccentric orbits by radiation pressure fills up the gap and populate it. Very fine structures can be modelled, however, DyCoSS is restricted to very specific setups where the system is at steady state under the influence of only one perturber, and as such shares some similarities with the CGA code (Stark & Kuchner 2009). On top of this, the coupling between dynamics and collisions is only partial as collisions are fully destructive and the fate of collisional fragments is not followed over time. That is why our team decided to develop a totally new approach in parallel that overcomes all of these limitations.

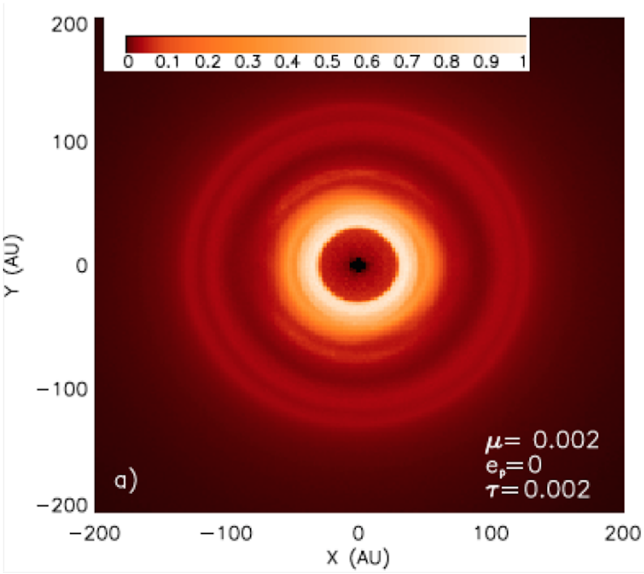

Fig. 1. The effects of a planet at 75 AU embedded within a broad disc (30-130 AU) modelled with a partial coupling code called DyCoSS (Thebault et al. 2012).

The most ambitious part of the PhD was to develop a new state-of-the-art code code, called LIDT-DD, which was the first to merge an N-body code to treat the dynamics of grains and a statistical model to handle dust collisions (Kral et al. 2013). This is a complex process as each collision can create millions of fragments that will themselves collide at the next time step and so on (Charnoz & Taillifet 2012). To make it work over long timescales, some new tools have been developed such as using super-particles (SPs) and many new ideas to be able to regulate smartly the number of SPs within the system, which would otherwise be unmanageable. A SP represents of cloud of particles having the same size and the same orbital parameters. Fig. 2 explains with a diagram how LIDT-DD works over one time step. This can be described in six distinct steps as we follow the evolution of each SP: 1) The orbit of the SP is evolved dynamically (accounting for radiation pressure forces and the gravity of star and surrounding planets), 2) A collisional grid is superimposed on the N-body simulation, 3) Within each cell of the grid, the relative velocities between each grain is worked out, 4) All the fragments resulting from the collisions are created, 5) A sorting algorithm distinguishes the fragments that are really distinct from each other and 6) merges them otherwise.

This new generation model is able, for the first time, to treat accurately and self-consistently dust in complex systems. It is coupled to a radiative transfer code for optically thin discs, which is called GRaTeR (Augereau et al. 1999), and synthetic observations can be produced to compare to actual observed images or spectra. This code opens numerous new possibilities, as it is now possible to follow the dust evolution accurately, in a wide range of systems, where both collisions and dynamics are important.

The first real astrophysical application of the code is the case of violent collisions between sub-planetary mass bodies (Kral et al. 2015). This type of collision is expected during the latest stages of planetary formation. An increasing number of observations show that some discs are too bright to be at collisional steady state given their age, and that some violent transient collisional events could have taken place (Johnson et al. 2012). Our new generation model is able to tackle such an arduous problem for the first time, and leads to some interesting results such as the brightness of such violent phenomena, their timescale, their detectability, as well as being able to predict infallible signature of such events. We perform the first fully self-consistent modelling of the aftermath of massive breakups in debris discs. The initial conditions used to realise this study are shown on Fig. 3. The central star is an A7V and we follow the collisional and dynamical evolution of dust released after the breakup of a Ceres-sized body at 6 AU from the star. This breakup creates rapidly an asymmetric dust disc that is homogenised, by the coupled action of collisions and dynamics, on a timescale of a few 10^5 years. It creates an excess of luminosity that should be detectable in mid-IR photometry, from a 30 pc distance, over a period of $\sim 10^6$ years that exceeds the duration of the asymmetric phase of the disc (of a few 10^5 years). We tried to quantify whether the long-lived asymmetric structures created after such an impact would be observable in a distant planetary system. We created synthetic images with the SPHERE/VLT and MIRI/JWST instruments,

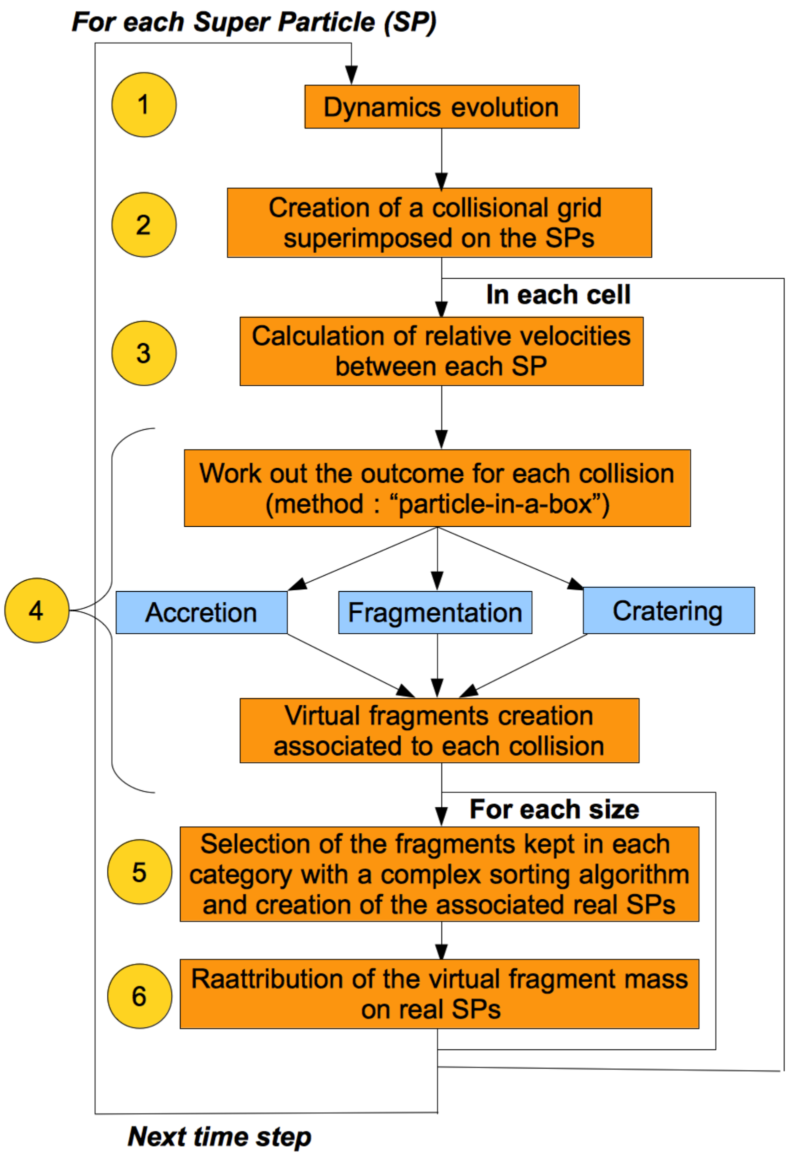

Fig. 2. Simplified diagram showing the time evolution of one time step in LIDT-DD (Kral et al. 2013).

showing that the asymmetries should be clearly visible and resolved from a 10 pc distance for SPHERE and at larger distances for JWST. Images at 1.6μm (marginally), 11.4 and 15.5μm would show the inner disc asymmetry at the collision point, while 23μm images would display the outer disc asymmetry in the dust halo, on the opposite side of the collision point (see Fig. 4). This double asymmetry is a well-defined signature that could be searched for. Confirmed detections of this signature would lead to actual observations of on-going planetary formation, which would be a major advance in our understanding of planetary formation.

3 Perspectives

The global idea of the future research that will be led with the results of this thesis, would be to extend our knowledge of observed planetary systems. This can be done on several fronts, such as having a better understanding of the mechanisms that form planetary systems, or such as trying to extract as much information

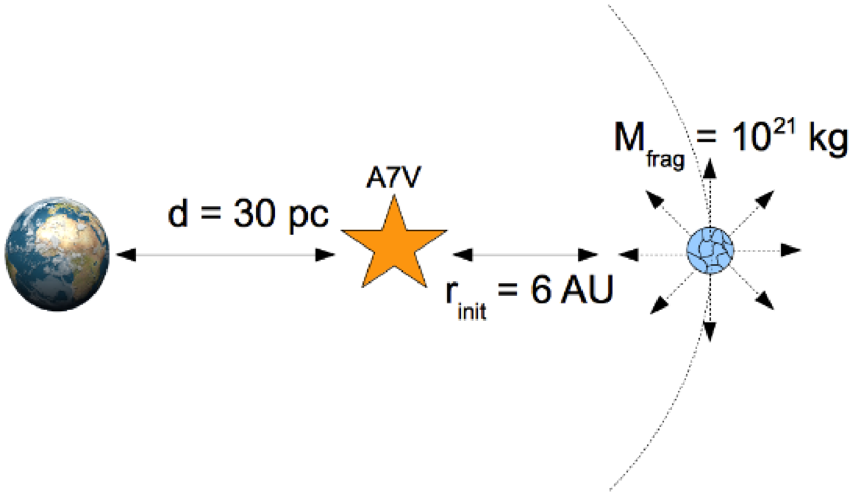

Fig. 3. Initial conditions of the LIDT-DD simulation used to model the aftermath of a massive collision between two asteroid-like objects (Kral et al. 2015).

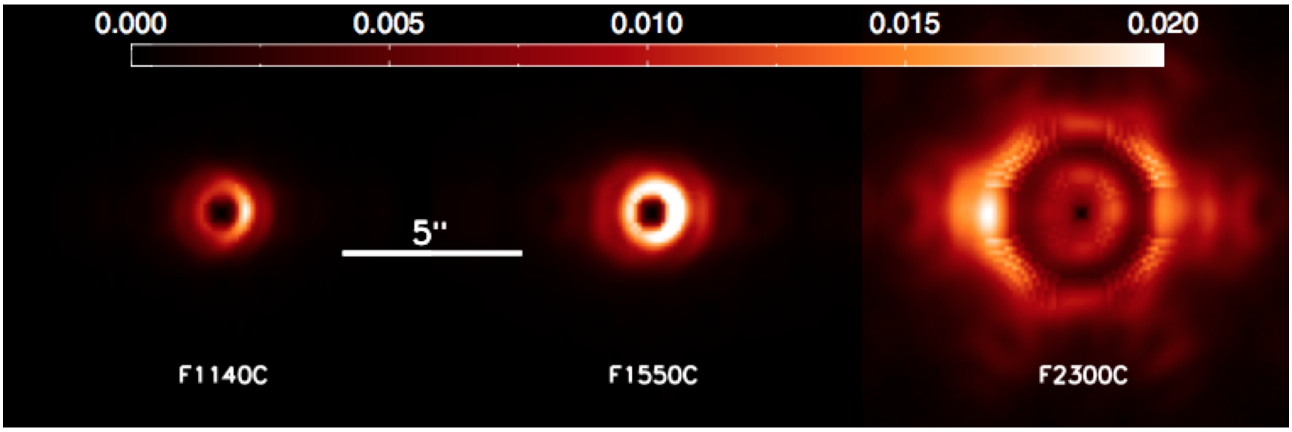

Fig. 4. JWST/MIRI synthetic observation of the aftermath of a massive collision between two asteroid-like objects. Simulation with LIDT-DD (Kral et al. 2015).

as possible from an ensemble of observations that are already collected. The model developed in the thesis, LIDT-DD, can tackle both fronts, and a few interesting problems that could be covered in the near future are presented briefly here below.

An obvious first endeavour would be to explore the full potential of the LIDT-DD code, by investigating very important issues regarding debris discs evolution, and planet formation scenarios that could not be quantitatively investigated with previous non self-consistent codes. A non-exhaustive list of such applications would be planet-disc interactions, the effect of a companion passage on the disc structure, the effect of a violent break-up in such a disc, etc. Another interesting phenomenon called collisional avalanches could also be investigated. It consists in studying the effect of unbound grains created far inside the inner edge of a debris disc (due to a violent break-up or evaporation) ejected quickly by radiation pressure forces and encountering particles from the disc at steady state. A bolting phenomenon or avalanche can be observed and could even possibly explain the recent mysterious observation (Melis et al. 2012), where a circumstellar disc totally disappeared on a very small timescale of about two years.

One of the most urgent problem to solve is the mystery of exozodiacal dust that should not exist so ubiquitously around so many old stars, as this hot dust lifetime is very short. It is a major issue as this hot dust can be within the habitable zone and prevent from observing the "holy grail" of planetary science: *habitable Earth-like planets*. Different scenarios that can create this hot dust have been proposed but could not be modelled numerically with previous codes. LIDT-DD could explore the different paths and bring some new clues concerning the survival of this dust, and in the end, help to observe beyond the dust shield that it forms to see the habitable Earth-like planets.

On a longer timescale, one could also imagine to extend this work to transitional discs (that are not well-understood) or even to a very different case, such as planetary rings. Future applications are numerous and very broad.

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