Dynamics of Small Bodies in Planetary Systems

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Abstract The number of stars that are known to have debris disks is greater than that of stars known to harbor planets. These disks are detected because dust is created in the destruction of planetesimals in the disks much in the same way that dust is produced in the asteroid belt and Kuiper belt in the solar system. For the nearest stars, the structure of their debris disks can be directly imaged, showing a wide variety of both axisymmetric and asymmetric structures. A successful interpretation of these images requires a knowledge of the dynamics of small bodies in planetary systems, since this allows the observed dust distribution to be deconvolved to provide information on the distribution of larger objects, such as planetesimals and planets. This chapter reviews the structures seen in debris disks, and describes a disk-dynamical theory which can be used to interpret those observations. In this way much of the observed structures, both axisymmetric and asymmetric, can be explained by a model in which the dust is produced in a planetesimal belt which is perturbed by a nearby, as yet unseen, planet. While the planet predictions still require confirmation, it is clear that debris disks have the potential to provide unique information about the structure of extrasolar planetary systems, since they can tell us about planets analogous to Neptune and even the Earth. Significant failings of the model at present are its inability to predict the quantity of small grains in a system, and to explain the origin of the transient dust seen in some systems. Given the complexity of planetary system dynamics and how that is readily reflected in the structure of a debris disk, it seems inevitable that the study of debris disks will play a vital role in our understanding of extrasolar planetary systems.

2.1 Introduction

Planetary systems are not just made up of planets, but are also composed of numerous small bodies ranging from asteroids and comets as large as 1000 km down to sub-micrometer-sized dust grains. In the solar system, the asteroids and comets are confined to relatively narrow rings known as the asteroid belt and the Kuiper belt (see chapters by Nakamura and Jewitt). These belts are the source of the majority of the smaller objects seen in the solar...
system, since such objects are inevitably created in collisions between objects within the belts (see chapter by Michel). Sublimation of comets as they are heated on approach to the Sun is another source of dust in the solar system.

It is known that extrasolar systems also host belts of planetesimals (a generic name for comets and asteroids) that are similar to our own asteroid belt and Kuiper belt. These were first discovered using far-IR observations of nearby stars, which showed excess emission above that expected to come from the stellar photosphere [5]. This emission comes from dust that is heated by the star and which reradiates that energy in the thermal infrared, at temperatures between 40 and 200 K, depending on the distance of the dust from the star. The lifetime of the dust is inferred to be short compared with the age of the star, and so it is concluded that the dust cannot be a remnant of the protoplanetary disk that formed with the star (see chapter by Takeuchi), rather it must originate in planetesimal belts much in the same way that dust is created in the solar system [7].

Over 300 main-sequence stars are now known with this type of excess emission [10, 50, 74], and such objects are known either as Vega-like (after the first star discovered to have this excess) or as debris disks. Statistical studies have shown that ~15% of normal main-sequence stars have debris disks, although it should be stressed that the disks which can be detected with current technology have greater quantities of dust than is currently present in the solar system by a factor of at least 10 [25]. Nevertheless, this indicates that debris disks are common, more common in fact that extrasolar planets which are found around ~6% of stars [18]. Studying these disks provides a unique insight into the structure of the planetary systems of other stars. Indeed, the nearest and brightest debris disks can be imaged, and such studies have provided the first images of nearby planetary systems. These images reveal the distribution of dust in the systems, which can in turn be used to infer the distribution of parent planetesimals, and also the architecture of the underlying planetary system. However, to do so requires an understanding of both the mechanism by which dust is produced in planetesimal belts and its consequent dynamical evolution, as well as of the dynamical interaction between planets and planetesimals and between planets and dust.

This chapter reviews our knowledge of debris disks from observations (Sect. 2.2) and describes a simple model for planetesimal belt evolution which explains what we see (Sect. 2.3), as well as how the detailed interaction between planets and planetesimals imposes structure on that planetesimal belt (Sect. 2.4), and how those perturbations translate into structures seen in the dust distribution (Sect. 2.5). Conclusions, including what has been learned about the planetary systems of nearby stars from studying these disks, are given in Sect. 2.6.