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Probing Exoplanetary Materials Using Sublimating Dust

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Summary

In the past few decades, it has become clear that the Sun is not the only star accompanied by planets. Extrasolar planets (exoplanets) have been detected around more than a thousand stars and their ubiquity indicates that planet formation is more the rule than the exception. Surprisingly, many of the discovered exoplanetary systems are very different from the Solar System in the types of planets they harbour and the distances from the host stars at which those planets orbit. These realisations have raised some exciting questions:

- Why does planet formation have such diverse results?
- What processes determine the architecture of a planetary system?
- How special is the Earth as a planet and the Solar System as a planetary system?
- Are there other places in the Milky Way galaxy where life could have emerged?

Finding answers to such questions is one of the goals of modern astronomy.

In order to address these questions, it is necessary to obtain detailed information about extrasolar systems through astronomical observations. However, the vast distances between stars, as well as the small size of a planet with respect to its host star, present major obstacles to characterising exoplanets. The majority of what we currently know about exoplanets comes from the effects planets have on their host stars.

However, a planetary system consist of more than just planets. Also orbiting the star is a wide range of smaller bodies, such as asteroids, comets, and interplanetary dust grains. The study of these materials can provide information about the planetary systems that cannot be inferred from the planets themselves. Circumstellar dust is particularly useful in this respect. A swarm of dust grains may constitute a very small percentage of the mass of a system, but its collective cross-section is enormous. This makes it possible for modern telescopes to directly observe the radiation emitted by an extrasolar cloud of dust, and in some cases even to distinguish its spatial structure.

Circumstellar dust grains usually have a relatively short lifetime, because they are removed or destroyed by several mechanisms. For example, the pressure associated with a star's radiation can blow very small dust grains away, out of the system. This means that for any dust to be present, it must be replenished continuously from larger bodies that constitute a more stable mass reservoir, for instance through destructive collisions between asteroids or comets that produce dust as fragments. Because circumstellar dust originates in larger bodies, the two populations are related in location and composition, and observations of dust can be used to probe exoplanetary materials.

To make the step from dust observations to inferring properties of an exoplanetary system, one must understand in detail how dust grains are produced, how they behave after being released, and how they are destroyed or removed. Understanding the physics of circumstellar dust is the subject of this thesis. The thesis focusses specifically on dust grains that orbit extremely close to their host star, at only a few stellar radii. At these distances, the dust is heated to temperatures so high that the solid material it consists of turns into vapour, a process called sublimation.

Sublimation can add some interesting complications to the life of a circumstellar dust grain. Most importantly, as a dust grain sublimates, it gradually loses mass and becomes smaller. Generally, smaller dust grains have a larger cross-section in proportion to their mass. This means that as a dust grain becomes smaller, the forces on the grain due to stellar radiation pressure become more important with respect to gravity. Such changes influence the movement of the dust grain. We investigate two particular situations in which dust sublimation is relevant: hot exozodiacal dust and the dusty tails of evaporating exoplanets.

Hot exozodiacal dust

Chapters 2 and 3 are concerned with the phenomenon known as hot exozodiacal dust. This is dust located in the close vicinity of a star that can be detected through specialised infrared observations. Some 10% to 30% of all stars seem to have such a population of dust, but its origin is still unclear.

In Chapter 2, we investigate a possible mechanism that could explain the phenomenon. The dust could be created by collisions in a belt of asteroids or comets further out, and dragged inward by forces caused by the stellar radiation and the orbital motion of the dust grains. Once the dust is very close to the star, it starts sublimating, which decreases the size of the dust grains. This brings about changes in the radiation pressure forces, causing the inward migration to slow down and hence leading to a pile up of dust grains around the sublimation distance from the star. Although the pile-up mechanism seems promising to explain the location of hot exozodiacal dust, our detailed investigation of this process reveals that it is inefficient. We conclude that the proposed mechanism cannot explain the observed quantities of dust.

Chapter 3 is an in-depth study of the dust in the close vicinity of the star Fomalhaut. This star is known to have belts of asteroids and comets that produce dust through mutual collisions. Infrared observations show that some dust also exists very close to the star. In this chapter, we derive the properties and spatial distribution of the dust in the inner parts of the

Fomalhaut system from the observations. Using this information, we check several possible mechanisms that could explain the presence of the dust, finding that none can provide dust in sufficient quantities to explain the observations. The origin of hot exozodiacal dust remains a mystery.

Dusty tails of evaporating exoplanets

Chapters 4 and 5 are about small exoplanets that orbit so close to their stars that they evaporate due to the intense stellar irradiation. Such planets emit large amounts of dust grains, which end up in a comet-like tail behind the planet. As these objects pass in front of their host star, the cloud of dust causes the star to temporarily appear slightly dimmer. Using an accurate astronomical instrument, this effect can be followed in detail. From the precise way in which the star dims, it is then possible to derive the shape of the dust cloud. At the moment, three of these small evaporating exoplanets are known.

We describe why dust grains that are ejected from the planet trail behind the planet, forming a tail. Put simply, because the dust grains are pushed outward by the radiation pressure of the star, they travel on orbits that are a bit larger than that of the planet, and consequently they take marginally longer to circle the star. Hence, the dust grains lag behind the planet and form a tail. As they slowly drift away from the planet, the dust grains gradually sublimate. If the dust grains are made of a refractory material, they will take long to sublimate and yield a long tail. Conversely, volatile dust species disappear quickly and give short tails. Therefore, the length of the tail, which can be derived from the duration of the dimming of the star, can be used to learn about the composition of the dust.

In Chapter 4, we study this astrophysical problem using pen-and-paper-type techniques. These are useful to gain a better understanding of the situation and provide quick answers, but they also require making many simplifying assumptions about the dust grains and their behaviour, which may not be accurate in some circumstances. Chapter 5 introduces a numerical model, which uses more elaborate computer calculations to determine the dust composition from the dimming of the star. This technique is slower and more cumbersome, but it uses less assumptions than the pen-and-paper method, and provides a more detailed answer.

The results of the two different analysis methods are consistent. We find that the dust in the tail of one of the investigated evaporating planets could be made of the mineral corundum, an aluminium oxide. It is the same material that rubies and sapphires are made of. The study also demonstrates that many other dust compositions, such as iron, graphite, and magnesium-rich silicates, are much less likely. Most importantly, this work shows that it is possible to distinguish between different compositions for the dust in the tails of small evaporating planets from the way their host star dims as they pass in front of it. Since the dust originates in the evaporating planet, it can be used to probe the composition of this type of exoplanets.