Light scattering in circumstellar disks

M. Min* and S. V. Jeffers

Astronomical institute, Univ. of Utrecht, P.O. Box 80000, NL-3508 TA Utrecht, The Netherlands.

Planets, asteroids and comets are born in disks of gas and dust surrounding newly formed stars. In these protoplanetary disks, tiny dust grains stick together to form larger bodies. How this happens and at what speed is a question we can address by carefully examining the light scattered and emitted by the dust grains in these disks. Over a timescale of $\sim$ 10 million years, the system evolves into a debris disk, i.e., a disk mainly composed of second-generation dust produced by collisions of larger bodies and outgassing of comets. These debris disks provide a unique view on what might have been the conditions in the early Solar system. Observations of these disks in scattered light provide a way to image the spatial distribution of the dust grains and, at the same time, obtain information on their sizes and structures. In this contribution, we will discuss observations and theoretical modeling of light scattered by dust grains and aggregates in these circumstellar disks. Effects of grain properties as well as effects of the disk geometry on the observables are discussed with a special focus on imaging polarimetry. Also, the computational and observational challenges we face when interpreting observations of the scattering properties of circumstellar dust are discussed.

DUSTY DISKS

It is generally accepted that the origin of grains in circumstellar disks is interstellar dust. Interstellar dust grains are considered to be small and composed of silicate and carbon [1]. In the gas-rich disks around young stars, these grains can coagulate to form larger aggregates. The growth of fluffy aggregates changes the observable signature from both scattered and emitted radiation in particular ways that are qualitatively well understood, though quantitative studies are usually restricted to small aggregates.

When the circumstellar disk evolves into a planetary system, the dust grains we observe are expected to change from the aggregates generally thought to dominate in protoplanetary disks to compact debris dust grains formed from collisions of larger bodies. These compact grains provide their own challenges to dust modelers. For example, effects of surface roughness and complex internal structure are of crucial importance for interpreting observations of scattered light [2]. Below we briefly discuss how scattered light and, in particular, imaging of scattered light, can be used to study the evolution from small grains to larger aggregates and planetesimals all the way to the collisionally formed debris found around main-sequence stars.

SCATTERED LIGHT IMAGING

Imaging protoplanetary disks or debris disks in scattered light is challenging as they are many orders of magnitude fainter than their central stars. The limited spatial resolution of the telescope causes the central star to dominate over the scattered light out to a large distance. There are two methods used to suppress the radiation from the central star: coronographic

*Corresponding author: Michiel Min (M.Min@astro-uu.nl)

imaging, where starlight is blocked by a disk in the optical setup, and polarimetric imaging, where only the scattered light from the star's circumstellar environment is detected.

Coronographic imaging

Coronographic imaging has been successfully used to image numerous circumstellar disks, both protoplanetary and debris disks. The images of protoplanetary disks show rich spatial structure, e.g. spiral arms [3]. The images of debris disks often display ringlike structures, not unlike the Kuiper belt in our Solar system (see, e.g., [4]). The albedo of the circumstellar material around debris disks can be determined from coronographic images combined with the dust's spectral energy distribution. For some debris disks, (e.g., [4]), this results in a relatively low (a few percent) value, consistent with the albedo of some types of asteroids. Additionally, scattered light images provide information on the phase function over quite a large range of scattering angles simultaneously. An example of this is the well-studied debris disk around Fomalhaut. Interestingly, it was found that the grains in this system appear to be dominantly backward scattering[5], which can be explained by very large, rough particles or compact agglomerates[2].

Polarimetric imaging

The physics behind polarimetric imaging is that starlight reflected from circumstellar material becomes linearly polarized. By imaging linearly polarized light, it is possible to clearly discriminate between scattered light from circumstellar environments and unpolarized light from the central star. Already, some polarimetric images of protoplanetary disks are available (see, e.g., [6]). Also, polarimetry has already been used for quite some time to study nearby debris disks (see, e.g., [7]).

MODELS OF DISKS

The observed intensity or polarimetric signal from a circumstellar disk depends foremost on the optical properties of the dust grains in the disk. Many studies analyzing polarimetric measurements today still use spherical particles as their dust grain model (see, e.g., [8]), even though the light-scattering community is well aware of the shortcomings of this particle shape model. Besides the optical properties of the grains, one needs to consider the geometry of the circumstellar disk as well. Gas-rich protoplanetary disks around young stars are optically very thick and, thus, multiple scattering and radiative transfer are essential when modeling these disks.

It is usually assumed that protoplanetary disks are in vertical hydrostatic equilibrium. In order to compute this, one needs to know the temperature structure. For this, the optical properties of the dust grains are needed over a very wide wavelength range. This is one of the key problems in applying advanced particle scattering tools to fully model protoplanetary disks, since most advanced methods cannot provide accurate optical properties all the way from the visual to the millimeter part of the spectrum.

Modeling polarimetric images

As an example of how dust optical properties and disk geometry both influence observables, we focus now on polarimetric imaging. This is a technique gaining in popularity which, when

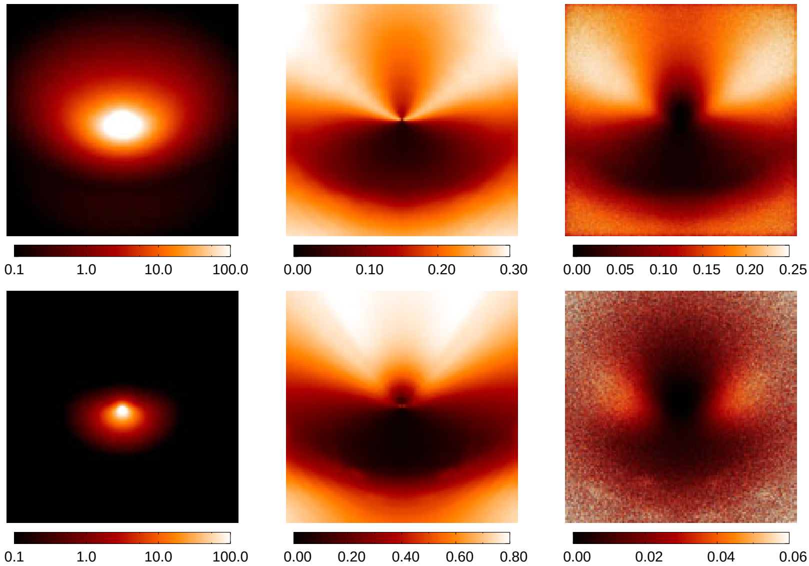

Figure 1. The total intensity (left) and degree of linear polarization (middle, and right) image of a flaring protoplanetary disk with compact grains (upper panels) and fluffy aggregates (lower panels). The size distributions of the grains are chosen such that the spectral energy distribution of the model with compact grains and that of the model with fluffy aggregates are almost identical. The rightmost image is convolved with the response of a 4-m telescope with effects of atmospheric seeing and noise added corresponding to a few hours integration.

properly used, will allow us to lift many degeneracies currently encountered in interpreting disk observations.

The degree of polarization of the light scattered by the circumstellar matter provides additional, independent constraints on the size and shape of the particles in the disk. As an example in the leftmost four panels of Fig. 1, we present model images of two protoplanetary disks. The first model, presented in the upper panels, contains compact particles (computed using the Distribution of Hollow Spheres [9]) with sizes between 0.1 and 1 µm. The second model, presented in the lower panels, contains fluffy aggregates (computed using the Aggregate Polarizability Mixing Rule [10]) with sizes between 0.1 and 10 µm. In both cases, the central star is a Herbig star ($M_\star = 2.5\,M_\odot$, $T_{\rm eff} = 10000\,$K) surrounded by a disk with a dust mass of $M_{\rm dust} = 10^{-3}\,M_\odot$. The disk is in vertical hydrostatic equilibrium and extends from the dust evaporation radius out to 200 AU after which the surface density drops exponentially. Both models show a very similar spectral energy distribution, and almost identical infrared emission spectrum. However, it is clear that in polarized light the models can be easily distinguished (also note the difference in absolute scaling of the two polarization images). This is because the two types of grains have very different scattering characteristics.

In the rightmost two panels of Fig. 1, we show the degrees of linear polarization as they would be observed with a 4-meter class telescope from the Earth (i.e., including smearing due to diffraction at the telescope and atmospheric effects). It is clear that the image changes dramatically. Especially, the simulated observation with fluffy aggregates looks quite different from the initial model image. This is because for this model the scattering phase function is much more forward peaked so that most radiation is scattered outside the view of the observer. Therefore, the depolarizing effect of the stellar point spread function is much stronger. So although the degree of polarization from the fluffy aggregates is intrinsically much higher than that of the compact grains, the actual observed degree of polarization is much lower. Methods have to be developed to disentangle these effects in order to properly interpret upcoming polarimetric imaging observations.

CONCLUSIONS AND PERSPECTIVE

Scattered light imaging provides a powerful diagnostic tool to study the evolution of protoplanetary to debris disks. With the proper analysis tools, it allows a determination of the sizes and structures of the dust particles and their spatial distribution. The need for optical properties of large complex aggregates and compact grains over a broad wavelength range and with relatively high values of the refractive index challenges the light-scattering community to come up with accurate and efficient computational tools. The additional constraints obtained from the polarimetric images of circumstellar disks are needed to lift the degeneracies of interpreting intensity observations. Examples of current and upcoming polarimeters are ExPo at the 4.2-m WHT, SPHERE at the 8.2-m VLT, and EPICS at the 42-m ELT. Our view on circumstellar dust is going to change dramatically with these new, sensitive polarimetric imagers.

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