Observational evidence for dust growth in proto-planetary discs

Gwendolyn Meeus

AIP, An der Sternwarte 16, D-14482 Potsdam, Germany

Abstract. The dust in the interstellar medium, that provides the material for forming stars - and circumstellar discs as a natural by-product - is known to have submicron sizes. As these discs are the sites of planet formation, those small grains are predicted to grow to larger entities when the stars are still young. I will review evidence for the first steps in grain growth in proto-planetary discs around young stars, based on recent Spitzer and ground-based infrared observations. First, I will discuss disc and dust properties in Herbig Ae/Be stars, and then move to the lower-mass T Tauri stars and the brown dwarfs. Here, objects of different star-forming regions are compared, and the influence of the stellar parameters and environment on dust evolution, as witnessed by the observed dust characteristics, is discussed.

1. Introduction

The research of dust growth in the disc of young stellar objects is motivated from the observations of dust in the interstellar medium (ISM): Kemper et al. (2004) showed that the crystalline fraction of the ISM dust is smaller than 2%, and the size of the amorphous silicates is smaller than 0.1 micron (see Fig. 1, left panel). It is this dust that eventually will constitute the proto-planetary disc, so that, initially, the dust grains in circumstellar (CS) discs must have small sizes too. However, as planets are expected to form in these discs, the grains will have to grow to larger sizes, forming planetesimals, and finally planets. This process, however, is not yet well understood, especially not the timescale over which it happens, or which physical properties of the star or the environment would impede or hasten the growth of dust particles. It is these first steps of grain growth, from submicron sizes to sizes of a few microns, that I will discuss in this paper.

First, we will give a short introduction into the mineralogy of astronomical dust, and show how we can retrieve information about the dust properties from infrared spectroscopy. In a next step, we will discuss the disc and dust properties of the bright Herbig Ae/Be stars, and then we will apply the same technique for the solar-mass T Tauri stars and the substellar mass brown dwarfs.

2. Mineralogy in a nutshell

Astronomical dust is either oxygen or carbon rich. Oxygen-rich dust particles are mainly silicates, which can be either iron or magnesium-rich, have a crys-
Figure 1. Left: The optical depth towards the galactic center is clearly caused by small, amorphous silicate grains, as indicated by the shape observed (Kemper et al. 2004). Right: Absorption coefficients of amorphous silicates with a pyroxene and olivine stoichiometry, in 3 different sizes that are relevant in the 10 micron window (Dorschner et al. 1995). Solid line: 0.1 micron, dashed line: 1.5 micron and dashed-dotted line: 6.0 micron. With increasing size, the feature shifts towards longer wavelengths with an increasingly important red shoulder, and flattens.

talline or amorphous structure, and a wide variety in shapes and sizes. In the 10 micron observational window, the most important dust species such as pyroxenes, olivines and silica show features that can be used to derive their size, composition and structure (see Fig. 1 for an example of pyroxene and olivine features). For this purpose, optical constants that are measured in the lab are of great importance (e.g. Tamanai et al. 2006).

3. Herbig Ae/Be Stars

Infrared spectroscopy knew a large step forward through the launch of the Infrared Space Observatory (ISO). For the first time, the dust in circumstellar discs could be studied in detail. In particular, the discs of the bright Herbig Ae/Be stars, a class of pre-main sequence stars with spectral type A or B that are marked by the presence of the Hα emission line and an IR excess due to dust, were studied extensively between 2 to 45 micron. The dust particles that emit in this wavelength region are warm (a few 100 K), and are located in the optically thin disc atmosphere. The bulk of the disc material, however, is cold (below 100 K) and resides in the midplane of the disc, which is optically thick, hence invisible to us.

ISO unveiled a wide variety of dust features in Herbig Ae/Be stars: different shapes and strengths, pointing to a wide range in grain size and crystallinity were observed (Meeus et al. 2001; Bouwman et al. 2001). In Fig. 2, we give a few examples of the emission features observed in the 10 micron window. van Boekel et al. (2003) further related the 10 micron feature strength and shape (triangular versus a more flattened shape) at 10 micron to the grain size of the silicates, with the aid of laboratory spectra, and found clear evidence for grain growth in HAEBEs.
Figure 2. The 10 micron feature for a sample of Herbig Ae/Be stars. They show a wide variety in shape and strength, pointing to the presence of both small and large grains in their discs, with a varying amount of crystallinity (Meeus et al., 2001).

Figure 3. The spectral energy distributions of selected Herbig Ae/Be stars. The slope in the millimetre region is much steeper for AB Aur than for HD163296, pointing to larger cold grains for the latter star (Meeus et al., 2001).
Radiative transfer models of the disc structure and evolution predict that when small grains, located in the disc atmosphere, grow to larger particles, they will gradually settle towards the disc midplane. This will be accompanied by a flattening of the (initially) flared disc (Dullemond & Dominik 2004). This process has been confirmed through observations: objects which have a smaller mid-IR excess (pointing to a less flaring disc) on average have a shallower slope at millimetre wavelengths, indicating larger sizes for the cold grains (Acke et al. 2004).

4. T Tauri Stars

T Tauri stars are the lower-mass counterparts of the Herbig Ae/Be stars, with spectral types between G and M, thus temperatures below $\sim 6000$ K. Recent Spitzer observations allowed for a characterisation of a large sample of T Tauri stars, thanks to its good sensitivity. It soon became clear that T Tauri stars have similar dust properties as the Herbig Ae/Be stars, although they have much smaller luminosities: some objects show nearly unprocessed dust, while others show larger grains and a substantial amount of crystalline silicates (Meeus et al. 2003; Kessler-Silacci et al. 2006).

In an unbiased sample of 12 TTS in the star forming region MBM12, with an age of 2 Myr, dust processing was also observed in different stages (Meeus et al. 2009). In Fig. 5 we show the relation between the shape and the strength of the 10 micron feature, indicating grain grows in these TTS discs. We derived the properties of the dust causing the 10 micron feature by modelling the feature, using the two layer temperature distribution method (TLTD) by Juháš et al. (2008) and including the following dust species in the fit: amorphous silicates, forsterite, enstatite and silica, in sizes of 0.1, 1.5 and 6.0 micron. We found that those objects that have the latest spectral types (lowest temperatures), tend to have the largest grains (see Fig. 5), a relation that was first remarked by Kessler-Silacci et al. (2006). This is merely because, when observing at 10 micron - tracing dust grains with temperatures of a few hundred Kelvin - we trace a region that is much closer in for those objects which have a lower luminosity.
Dust Growth: Observations

Figure 5. The shape of the 10 micron feature, determined by the flux ratio at 11.3 and 9.8 micron, in function of the feature strength, determined by the peak over continuum ratio for T Tauri stars.

Figure 6. The size of the amorphous silicates, as determined by the TLTD fit, in function of the spectral type (left) and the Hα equivalent width (right). Although the sample is really small, we do see a trend between both variables: the later the spectral type, the larger the grains observed, and the stronger the Hα line, the larger the grain sizes.

than for those with a higher luminosity. For instance, for T Tauri stars, this is of the order 0.5 AU, while for Herbig Ae stars, radial distances of a few AU are reached. When one, furthermore, considers that the density in the disc decreases with radial distance from the central star, and that grain growth increases with density, then it is natural to expect that the lower luminosity sources show more grain growth, when observing the 10 micron region (Kessler-Silacci et al. 2007).

In MBM12, the degree of flaring, as derived from the flux ratio at 24 and 8 micron is found to relate to the grain size, as derived from the 10 micron feature (Meeus et al. 2009). Furthermore, those sources that are most turbulent and accreting, as indicated by the equivalent width of the Hα feature, are found to host the largest grains in their disc atmosphere, while the lowest-accreting source have more ISM-like silicates (see Fig. 6), as was already noted by Sicilia-Aguilar et al.) (2007) in another sample of T Tauri stars.
5. Brown Dwarfs

Even for the very faint brown dwarfs, Spitzer provided spectra, but only for small samples. In Chamaeleon I, with an age of 2 Myr, 6 out of 8 brown dwarfs show an IR excess, but the amount of flaring is quite low for most of them. Both grain growth and crystallisation is observed to occur routinely in this sample (Apai et al. 2005), which might be attributed to their low luminosity: in the innermost regions of their discs, where the 10 micron radiation originates for brown dwarfs, it is likely that most of the dust has grown to larger sizes. However, the large crystallinity observed could also (partly) be a contrast effect, as larger grains cause weaker spectral features, so that the crystalline features become more clear. Only at an age of a few Myrs older, the discs and dust around brown dwarfs appear to have evolved drastically: in the star forming region Upper Scorpius, with an age of 5 Myr, most discs are flat, pointing to a large degree of dust settling, while the 10 micron feature is mainly absent or, in the rare case it is present, very weak (Scholz et al. 2007). At an age of 10 Myr, the brown dwarfs do not even show the feature anymore (Morrow et al. 2008). These observations show that dust and disc evolution around brown dwarfs occurs on a much faster timescale than in T Tauri stars or Herbig Ae/Be stars.

6. Conclusions

When discussing disc and dust evolution, parameters that come to mind as likely important players are age and effective temperature. Infrared spectral observations, however, have shown that probably some of those are not that important, and that the whole picture is more complex.

We presented observations of young objects with a wide range in masses (or temperatures). In all groups, the discs are observed to show a variety in degree of flaring, and also the dust features observed are both from unprocessed and processed grains, as witnessed by their derived sizes and crystallinity.

The lower the mass, the faster both the disc and dust evolution seem to happen: for brown dwarfs most discs are flat already at an age of 5 Myr, while the dust grains already have grown beyond a few microns at that age. Is this because discs evolve from the inside, and in brown dwarfs we see the more inward regions?

For the T Tauri stars, there is a clear relation between the strength of the 10 micron feature (a measure of the size of the emitting grains) and the spectral type: later spectral types, on average, harbour larger grains. Also the amount of accretion, as determined by the Hα feature, is an indicator of the dust properties: those sources that accrete most, hence have more turbulent discs, show the largest grain sizes in their disc atmospheres.

For the Herbig Ae/Be stars, we did not find a relation between their age and the amount of dust processing. This could be attributed to the difficulties to determine their ages, as they are mostly isolated.
7. Future directions

Obvious future steps will include a comparison of (1) the 'average' dust properties between clusters with different ages, densities and even metallicities, and (2) in more detail, between young objects located within the same cluster, hence with the same initial conditions. It is only when a meaningful statistical sample is obtained, that one can pinpoint those properties that influence dust processing, by keeping certain variables, e.g. environment and spectral type, as a constant. The large database of spectra that Spitzer has provided, will certainly help to solve (pieces of) the puzzle.

Also longer wavelength studies are important to derive the composition and temperature of the dust, in particular for olivines at 69 micron; it is in this context that Herschel will play an important role in the coming years.

Finally, higher spatial resolution will allow to search for the radial dependency of dust properties within a disc, it is here that interferometers are important. And last but not least, adaptive optics can help to resolve binaries, so that the influence of close companions on dust and disc evolution can be properly studied.

Acknowledgments. Part of this work was supported by the Deutsche Forschungsgemeinschaft (DFG) under project number ME2061/3-2.

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