Earth Moon Planets (2011) 108:45–50
DOI 10.1007/s11038-010-9374-z

Observational Evidence for Grain Growth

Gwendolyn Meeus

Received: 24 October 2008 / Accepted: 16 November 2010 / Published online: 18 December 2010

Abstract Discs around young stars are the sites of planet formation. The first step in this process is the growth of submicron grains to larger sized grains. I will review evidence for dust growth in CS discs, based on *ISO* and *Spitzer* infrared spectroscopic observations. Intermediate-mass stars, solar-type stars and even brown dwarfs will be discussed in the context of dust evolution. Furthermore, I will compare objects of several star-forming regions of different ages, and discuss the influence of the stellar parameters and environment on dust evolution, as witnessed by the observed dust characteristics. The main focus lies on what one can learn from 10 micron spectroscopy, the region where most astronomical dust species have important spectral features.

Keywords Stars formation · Planet formation · Circumstellar discs · Infrared

1 Introduction

The material that composes the circumstellar disc of a newborn star originates from the interstellar medium (ISM), so we expect its properties to be the same, at least initially. In the ISM, the dust grains are observed to be largely 'unprocessed': their sizes are smaller than 0.1 micron, and the crystalline fraction is smaller than 2% of the total mass [1]. However, it is in these discs that planets form, thus that grains grow to larger sizes and eventually planetesimals. It is not clear, on what timescale this happens, nor what stellar or disc properties would impede or hasten grain growth.

We first give a short introduction into mineralogy, to discuss the main astronomical dust species, and then show how we can retrieve information about the dust properties, using the bright Herbig Ae/Be stars as an example. Then we will apply the same technique for the lower mass T Tauri stars and finally the brown dwarfs, in clusters of different ages: Chamaeleon I, MBM12 and Upper Scorpius.

G. Meeus (✉)
Universidad Autonoma de Madrid (UAM), Dpt. Fisica Teorica,
Campus Cantoblanco, 28049 Madrid, Spain
e-mail: gwen@gmeeus.be

2 Mineralogy in a Nutshell

Astronomical dust can be divided in two main groups: oxygen-rich dust, e.g. silicates, and carbonaceous dust, e.g. polycyclic aromatic hydrocarbons (PAHs). We will only discuss oxygen-rich dust, consisting mainly of olivines, $Mg_{2x}Fe_{2(1-x)}SiO_4$, and pyroxenes, $Mg_xFe_{(1-x)}SiO_3$, with varying amounts of iron and magnesium content. The amorphous silicates can become crystalline through thermal annealing at a temperature of 700–800 K and higher.

The most common astronomical dust species are found to show important features around 10 micron, from which their size, composition and structure can be derived (see Fig. 1). This is only possible, however, when optical constants of the relevant dust species are available from laboratory experiments, e.g. [2].

3 Herbig Ae/Be Stars

Pre-main sequence stars, with masses between 2 and 8 $M_\odot$, showing Hα emission and an IR excess due to dust are called Herbig Ae/Be stars (HAEBEs). Radiative transfer models describe their discs with an optically thick midplane in which the bulk of the mass resides, surrounded by an optically thin hot surface layer. The discs are often flaring, supported by the hydrostatic equilibrium of the gas (e.g. Dullemond and Dominik [6]). The infrared space observatory *ISO* provided for the first time high quality infrared spectra of HAEBEs. The emission features observed at 10 micron are caused by warm dust grains in the optically thin surface layers of the disc. This means that the bulk of the dust mass, located in the disc midplane, remains invisible at those wavelengths. However, it is still interesting to study the 10 micron region, as it can constrain dust evolution taking place in those areas.

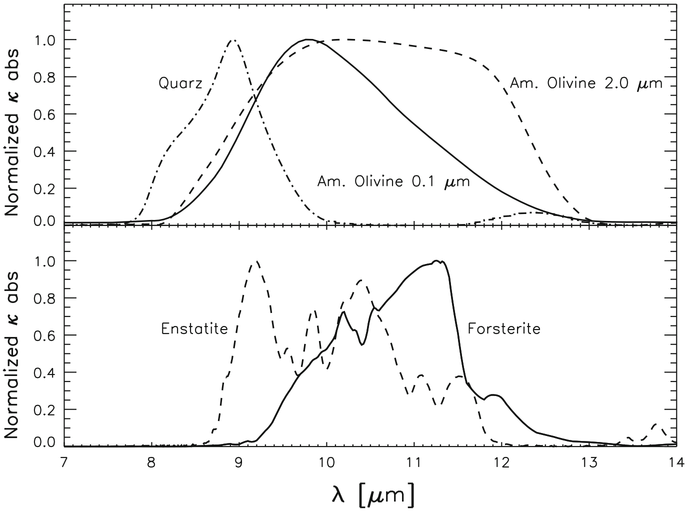

Fig. 1 Absorption coefficients of the main astronomical dust species in the 10 micron window. *Upper panel* the effect of increasing grain size for amorphous silicate is a widening of the feature towards longer wavelengths. *Lower panel* crystalline silicates, such as enstatite and forsterite, are identifiable through their sharp features at characteristic wavelengths

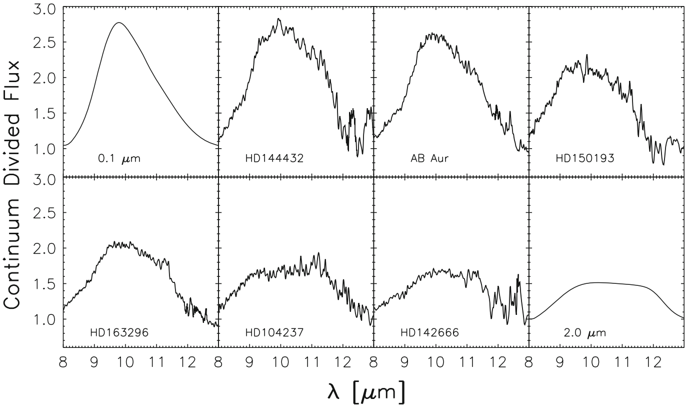

Fig. 2 Continuum divided silicate features of Herbig Ae/Be stars, ordered by strength from *left to right*, *top to bottom*. For comparison, we also show the absorption coefficients for amorphous silicates with sizes of 0.1 and 2.0 μm

With *ISO*, a variety of feature shapes was observed in HAEBEs: some are rather narrow, similar to ISM dust, while others are broader and/or show sharp peaks due to crystalline dust (see Fig. 2; [3, 4]). Van Boekel et al. related the 10 micron feature strength and shape to the size of silicates, and found evidence for grain growth in HAEBEs [5]. In Fig. 2, we plot the spectra of the HAEBEs, ordered by feature strength, and for comparison, amorphous silicate of different sizes. It is clear that grain processing has occurred in these objects in varying amounts.

Theoretical models of disc evolution predict that when small grains, located in the disc atmosphere, grow to larger particles they will gradually settle towards the midplane. This will be accompanied by a flattening of the (initially) flared disc [7]. This effect was observationally confirmed: objects with a smaller mid-IR excess—indicative of a flatter disc—have a shallower slope in the millimetre region, indicating larger sizes of the cold grains [8].

4 T Tauri Stars

The lower-mass analogues of HAEBEs are called T Tauri stars (TTS, with spectral types between G and M). IR spectroscopy showed that TTS have similar dust properties as the Herbig Ae/Be stars, although they have much lower stellar temperatures: some objects have features reminiscent of nearly unprocessed dust, while other show features indicative of larger grains and crystalline silicates; a wide variety can be observed, even when comparing stars with a similar age and spectral type (e.g. [9]).

MBM12 is a star-forming cloud, containing at least 12 TTS with spectral types between K3 and M6, and an age of 1–3 Myr. *Spitzer* observed the full sample in MBM12 and found evidence for dust processing at different stages [10]. The 7–17 micron region was modelled using a dust model with a two-layered temperature distribution (TLTD; [11]), and the following species: amorphous olivines and pyroxenes, crystalline enstatite and forsterite, and silica, all in three size regimes (0.1, 1.5 and 6.0 μm). In Fig. 3, we show a few examples typical of our sample, together with their best fit by the TLTD method.

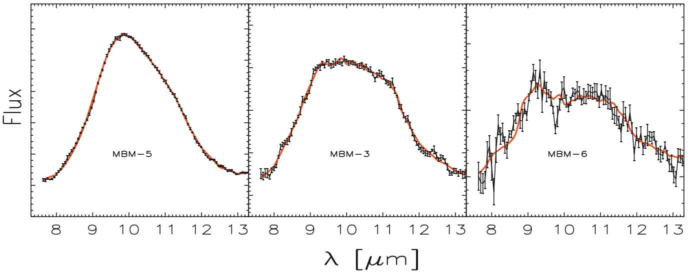

Fig. 3 Characteristical examples of 10 micron spectra in the sample of T Tauri stars, overplot with the best fit by the TLTD method (grey line)

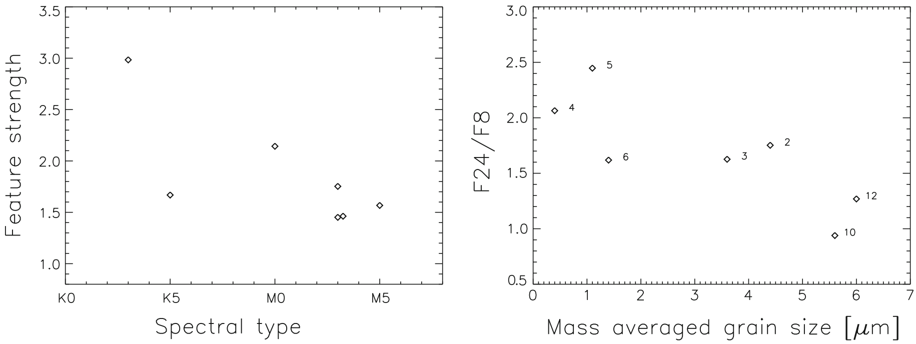

Fig. 4 *Left* 10 micron feature strength versus spectral type. The trend that later type stars show weaker features is also visible in this small MBM12 sample. *Right* Amount of flaring (as indicated by the flux ratio) versus mass averaged grain size. Flatter discs (smaller flux ratio) tend to have larger grains at 10 micron

In Fig. 4, we show that those objects that have the latest spectral types tend to have the largest grains, a relation that was first reported for another sample of TTS [12]. This relation can be understood when one considers that when observing dust at 10 micron, the emitting grains need to have a temperature of a few hundreds of Kelvin. The region in the disc where this temperature will be reached will be at a smaller radial distance for lower luminosity objects. As, furthermore, the density distribution decreases with radius, and grain growth increases with density, lower luminosity sources are thus expected to show larger grains in the IR, as that will originate in a denser region [13].

We also related the degree of flaring, as derived from the flux ratio at 24 and 8 micron to the mass-averaged grain size, as derived from fitting the 10 micron spectra with the TLTD method (see Fig. 4). Those sources that have the largest grains in the disc atmosphere tend to have the smallest amount of flaring, giving evidence for dust settling to occur routinely in T Tauri stars even at the young age of 2 Myr.

Furthermore, it was found that those sources that are most turbulent and accreting—normally the youngest ones—host the largest grains in their disc atmosphere, while the lowest-accreting source have ISM-like silicates [14]. This counter-intuitive relation (most active, probably youngest objects have largest grains) shows that yet another stellar parameter needs to be taken into account, when determining those variables that influence grain processing. This effect should be studied on a larger sample of T Tauri stars.

5 Brown Dwarfs

The high sensitivity of *Spitzer* even allowed us to study the disc and dust properties of the faint brown dwarfs. A sample of 8 brown dwarfs was observed in ChaI (2 Myr). The dust shows a high degree of processing, suggesting that crystallisation occurs on a large scale even in discs around objects of low (less than 3,200 K) temperatures [15]. However, the high degree of crystallinity could also be a contrast effect, as the weak silicate feature due to large grains would enhance the crystalline features. Furthermore, various degrees of flaring was observed, with a preference for flatter discs.

Only a few Myrs later, the discs and dust around brown dwarfs seem to have evolved drastically: in Upper Scorpius, at an age of 5 Myr, most discs are flat, pointing to dust settling, while the 10 micron silicate feature is mainly absent or, when present, very weak [16]. Brown dwarfs in the TW Hydrae association, with an age of 10 Myr, have flat discs and do not even show the feature anymore [17]. Disc and dust evolution towards flatter discs and larger grains appear to happen very fast in brown dwarfs, when compared with the higher-mass stars.

6 Conclusions

We used infrared photometry and spectroscopy of *ISO* and *Spitzer* missions to discuss disc and dust evolution in three different samples: intermediate-mass Herbig Ae/Be stars, the lower-mass T Tauri stars and brown dwarfs. We looked for relations between the stellar properties (such as age, spectral type,…), disc properties (such as amount of flaring) and properties of the warm dust, as derived from the 10 micron region. In all mass ranges of the central objects, discs are observed to be both flat and flaring, showing no relation with age or luminosity. Different degrees of dust processing is observed even at the youngest ages and smallest masses.

The best statistics are obtained for the T Tauri stars, as they have the largest samples that have been observed with *Spitzer*. A relation was found between the silicate grain size and the spectral type: the later the spectral type, the larger the grain size. This is probably a luminosity effect, as we look closer in towards the star for less luminous objects. Furthermore, we found a trend between amount of flaring and grain size: those objects which have the least amount of flaring tend to have the largest grains. Another, tentative relation has been proposed: objects which have the most turbulent discs (normally the youngest), show the largest grains. More observations of larger samples are needed to study this counter-intuitive relation.

The lower the mass, the faster both the disc and dust evolution seem to happen: for brown dwarfs most discs are already flat at an age of 5 Myr, while the dust grains also have grown beyond a few microns at that age, so that the silicate feature has become invisible. However, this could be a bias effect, as it might simply be that disc and dust evolution occurs first in the innermost regions, so that the lower the luminosity of the source one observes, the more evolved the disc and dust appears to be.

7 Future Directions

The next obvious step in the context of disc and dust evolution around young stars and brown dwarfs is to make statistically significant studies: the high sensitivity of *Spitzer* finally makes this approach possible. The influence of certain stellar parameters can be verified by comparing only those sources of e.g. the same age and spectral type, keeping the amount of free parameters at a minimum. Also the influence of cluster environment can be studied in this context, as well as the influence of close companions on the disc and dust evolution. Another step forward can be taken by high spatial resolution observations, resolving the discs: it is here that interferometers (will) play a crucial role.

With the launch of *Herschel* in 2009, it will be possible to also study the longer wavelengths, thus the cooler dust, in greater details. In this context, the forsterite feature at 69 micron needs to be mentioned, as it will allow to determine the dust temperature and composition of the olivines, while hydrous silicates can be studied at 100–110 μm.

Acknowledgments I would like to thank Th. Henning, J. Bouwman, A. Juhász, R. van Boekel and A. Sicilia-Aguilar for stimulating discussions. Part of this work was supported by the German *Deutsche Forschungsgemeinschaft, DFG* project number ME 2061/3-2.

References

1. F. Kemper, W.J. Vriend, A.G.G.M. Tielens, Astrophys. J. **609**, 826 (2004)
2. A. Tamanai, H. Mutschke, J. Blum, G. Meeus, Astrophys. J. **648**, L147 (2006)
3. G. Meeus, L.B.F.M. Waters, J. Bouwman et al. Astron. Astrophys. **365**, 476 (2001)
4. J. Bouwman, G. Meeus, A. de Koter et al., Astron. Astrophys. **375**, 950 (2001)
5. R. van Boekel, L.B.F.M. Waters, C. Dominik et al., Astron. Astrophys. **400**, L21 (2003)
6. C.P. Dullemond, C. Dominik, Astrophys. J. **560**, 957 (2001)
7. C.P. Dullemond, C. Dominik, Astron. Astrophys. **417**, 159 (2004)
8. B. Acke, M.E. van den Ancker, C.P. Dullemond, R. van Boekel, L.B.F.M. Waters, Astron. Astrophys. **422**, 621 (2004)
9. G. Meeus, M. Sterzik, J. Bouwman et al., Astron. Astrophys. **409**, L25 (2003)
10. G. Meeus, A. Juhász, Th. Henning et al., Astron. Astrophys. **497**, 379 (2009)
11. A. Juhász, J. Bouwman, Th. Henning et al., Astrophys. J. **721**, 431 (2010)
12. J. Kessler-Silacci, J.-C. Augereau, C.P. Dullemond et al., Astrophys. J. **639**, 275 (2006)
13. J. Kessler-Silacci, C.P. Dullemond, J.-C. Augereau et al., Astrophys. J. **659**, 680 (2007)
14. A. Sicilia-Aguilar, L.W. Hartmann, D. Watson et al., Astrophys. J. **659**, 1637 (2007)
15. D. Apai, I. Pascucci, J. Bouwman, A. Natta, Th. Henning, C.P. Dullemond, Science **310** 834 (2005)
16. A. Scholz, R. Jayawardhana, K. Wood et al., Astrophys. J. **660**, 1517 (2007)
17. A.L. Morrow, K.L. Luhman, C. Espaillat et al., Astrophys. J. **676**, 143 (2008)