ARTICLE IN PRESS
JID: YICAR [m5G;November 6, 2017;13:15]
Icarus 000 (2017) 1–17
Contents lists available at ScienceDirect
Icarus
journal homepage: www.elsevier.com/locate/icarus

Laboratory mid-IR spectra of equilibrated and igneous meteorites. Searching for observables of planetesimal debris

B.L. de Vries[a,b,c,*], H. Skogby[d], L.B.F.M. Waters[e,f], M. Min[e,f]

[a] Stockholm University Astrobiology Centre, Stockholm SE-106 91, Sweden
[b] AlbaNova University Centre, Stockholm University, Department of Astronomy, Stockholm SE-106 91, Sweden
[c] Scientific Support Office, Directorate of Science, European Space Research and Technology Centre (ESA/ESTEC), Keplerlaan 1, Noordwijk 2201 AZ, The Netherlands
[d] Department of Geosciences, Swedish Museum of Natural History, Box 50007, Stockholm SE-104 05, Sweden
[e] SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
[f] Astronomical Institute Anton Pannekoek, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands

A R T I C L E I N F O

Article history:
Received 11 January 2017
Revised 23 October 2017
Accepted 24 October 2017
Available online xxx

Keywords:
Meteorites
Mineralogy
Spectroscopy
Planetary formation
Debris disks

A B S T R A C T

Meteorites contain minerals from Solar System asteroids with different properties (like size, presence of water, core formation). We provide new mid-IR transmission spectra of powdered meteorites to obtain templates of how mid-IR spectra of asteroidal debris would look like. This is essential for interpreting mid-IR spectra of past and future space observatories, like the James Webb Space Telescope. First we present new transmission spectra of powdered ordinary chondrite, pallasite and HED meteorites and then we combine them with already available transmission spectra of chondrites in the literature, giving a total set of 64 transmission spectra. In detail we study the spectral features of minerals in these spectra to obtain measurables used to spectroscopically distinguish between meteorite groups. Being able to differentiate between dust from different meteorite types means we can probe properties of parent bodies, like their size, if they were wet or dry and if they are differentiated (core formation) or not.

We show that the transmission spectra of wet and dry chondrites, carbonaceous and ordinary chondrites and achondrite and chondrite meteorites are distinctly different in a way one can distinguish in astronomical mid-IR spectra. Carbonaceous chondrites type < 3 (aqueously altered) show distinct features of hydrated silicates (hydrosilicates) compared to the olivine and pyroxene rich ordinary chondrites (dry and equilibrated meteorites). Also the iron concentration of the olivine in carbonaceous chondrites differs from ordinary chondrites, which can be probed by the wavelength peak position of the olivine spectral features. The transmission spectra of chondrites (not differentiated) are also strongly different from the achondrite HED meteorites (meteorites from differentiated bodies like 4 Vesta), where the latter show much stronger pyroxene signatures.

The two observables that spectroscopically separate the different meteorites groups (and thus the different types of parent bodies) are the pyroxene-olivine feature strength ratio and the peak shift of the olivine spectral features due to an increase in the iron concentration of the olivine.

1. Introduction

Dust grains (micron-sized solid-state particles) play an essential role in many astrophysical environments. One of the prime examples is the formation and evolution of planets in proto-planetary disks. Small micron sized dust grains are the building blocks of planets. Proto-planetary disks are formed from interstellar dust and gas, where the lattice structure of the dust is amorphous and its composition is mostly silicate with some amounts of carbonaceous dust (Kemper et al., 2004; Min et al., 2007). In proto-planetary disks this dust can be annealed (the lattice structure is made crystalline due to heating) or it can be condensed from the gas (Tielens et al., 1997; Gail and Sedlmayr, 1999; Sogawa and Kozasa, 1999). Crystalline dust formation takes place in the inner parts of the disk. The crystals can subsequently be mixed with the outer parts of the disk (for example see Gail, 2004).

The crystalline and amorphous dust in proto-planetary disks can be studied by observing their emission and absorption in the infrared. Much can be learned about the composition, grain size

* Corresponding author at: Stockholm University Astrobiology Centre, SE-106 91 Stockholm, Sweden.
E-mail addresses: bldevries.science@gmail.com, b.devries@esciencecenter.nl (B.L. de Vries).

https://doi.org/10.1016/j.icarus.2017.10.029
0019-1035/© 2017 Published by Elsevier Inc.

and grain temperature of the crystalline dust in proto-planetary disks by studying and modelling their spectral features (Waelkens et al., 1996; Meeus et al., 2001; Kessler-Silacci et al., 2006; Sturm et al., 2013; Maaskant et al., 2015). The wavelength position, strength and shape of the spectral features show that the crystalline olivine ($[Mg,Fe]_2SiO_4$) grains are very magnesium rich (at most the olivine has an Fe/(Mg+Fe) of ∼ 0.0–0.03) and crystalline olivine is about 0–10% (by mass) of the total dust content in the disk. Besides olivine, pyroxene ($[Mg,Fe,Ca]SiO_3$) is also detected in crystalline form (Juhász et al., 2010). Although more difficult to determine, the pyroxene seems to contain more iron than the olivine (for pyroxene Bowey et al., 2007; Sargent et al., 2009; Juhász et al., 2010 report Fe/(Mg+Fe) values of 10–25%) and in some cases it can have an abundance equal to that of the crystalline olivine. Furthermore, Juhász et al. (2010) report that the pyroxene-over-olivine ratio decreases as a function of radius in the disk, which is difficult to explain based on equilibrium considerations (Gail, 2004).

In proto-planetary disks dust grains are used to form planetesimals and eventually planets. When the proto-planetary disk eventually sheds its gas and small dust grains a main-sequence star with a system of planetesimals and planets is left (Wyatt, 2008). During this evolution of the disk the minerals in the planetesimals and planets are influenced by parent-body processes. Depending on the properties and formation process of the parent-body these processes can be aqueous alteration, equilibration and melting due to heating (Hutchison, 2004). Relatively small planetesimals (several to a hundred of kilometres in diameter) can heat up several hundreds of Kelvin due to radiative decay of unstable elements (like ^{26}Al), during which diffusion between minerals can alter their composition (Kessel et al., 2007). Larger planetesimals (several hundreds of kilometres and up in diameter) and planets reach temperatures where the minerals melt and the body will differentiate (formation of a core and rocky crust), which has a strong influence on the composition and lattice structure of the minerals. An example of such a planetesimal in our Solar System is the asteroid 4 Vesta (Consolmagno and Drake, 1977; McCord et al., 1970).

The composition of planetesimals can be studied over astronomical distances by observing dynamically active systems where planetesimals have a high probability of colliding and being ground down to micron-sized dust grains (Wyatt, 2008). These micron-sized dust grains can form so called debris disks. It is important to note that the dust in these debris disks does not come from the proto-planetary disk, but consists of a second generation of dust coming from collisions in the system. Dust grains in debris disks can then be studied by analysing their infrared spectral features. Olofsson et al. (2012) studied young main-sequence stars with dust relatively close to the star at several hundreds of Kelvin (distances comparable to the asteroid belt). They found olivine with an iron content Fe/(Mg+Fe) ∼ 0.2 and Py/(Ol+Py) ratios of 0.0–0.2, which compares well with Solar System asteroids (Nakamura et al., 2011). The dust produced in a Kuiper-belt like analogue in the system of the main-sequence star β Pictoris contains olivine that is very pure Mg-rich (Fe/(Mg+Fe)=0.01) and no pyroxene is found (Chen et al., 2007; de Vries et al., 2012). The debris in the outskirts of β Pictoris compares best with cometary olivine found by for example the Stardust mission (Zolensky et al., 2008).

How minerals change due to parent-body processing can be understood from the meteoritic record of our Solar System. The minerals in meteorites can be studied in detail and they can be linked back to their parent-bodies and their properties. For example ordinary chondrites are linked to relatively small and equilibrated asteroids, some carbonaceous chondrites have been aqueously altered and have been linked to wet relatively small asteroids and the HED (howardite–eucrite–diogenite) achondrites are an example of achondrites linked to the differentiated asteroid 4 Vesta (for an overview see Hutchison, 2004 and for the Dawn mission Russell et al., 2015). Considering the silicate minerals in meteorites, the dominant silicate in carbonaceous chondrites with low metamorphic grade (type 1 and 2) are hydrated silicates (from here on hydrosilicates). Silicates in ordinary chondrites have experience little (type 3) to severe (type 4 and up) alteration due to heat which increased their pyroxene abundance and increased the iron content of their olivine and pyroxene minerals (up to Fe/(Mg+Fe) ∼ 0.16–0.32 and 0.18–0.26 respectively, Van Schmus, 1969; Brearley and Jones, 1998). The pyroxene content of achondrite meteorites is very high (> 90 vol%) and besides pure pyroxene one also observes other phases like plagioclase (a solid-solution between albite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_8$), Hutchison, 2004).

Besides detailed compositional information, much work has been done on reflectance and emission measurements (in the optical and near-IR, and both of surfaces and in powdered form, for an overview see for example Hutchison, 2004). In this work we focus on transmission measurements of powdered meteoritic minerals in de mid-IR (5–25 µm). We focus on this method because it is directly comparable to observations of dust grains freed by parent body collisions in young planetary systems. This enables us to make a direct spectroscopic comparison between dust from Solar System asteroids and extra-solar planetesimals and thus learn about the properties and evolution of extra-solar planetesimals. Mid-IR spectra of powdered meteorites have been done by Morlok et al. (2010) (also see Morlok et al., 2012, 2014a, 2014b), Beck et al. (2014) and Molster et al. (2003). Morlok et al. (2012) has studied mid-IR spectra of several powdered achondrites and Morlok et al. (2014b) of several powdered chondritic meteorites. Beck et al. (2014) measured the mid-IR spectra of powdered carbonaceous chondrites. Mid-IR spectra of an interplanetary dust particles (IPD) and micrometeorites have been presented in, for example, Sandford and Walker (1985), Molster et al. (2003) and Bradley et al. (1999).

The goal of this work is to (1) complement the available sets of mid-IR spectra of powdered meteorites with missing chondritic and achondritic powdered meteorite spectra, (2) present an overview of the spectral properties of all powdered meteoritic mid-IR spectra that are available to date and study their differences and (3) define several quantitative measurements useful for determining the parent-body properties based on the dust and debris in astronomical environments. The first quantitative measurement on the spectra that we consider in this paper is the relative strengths of the pyroxene and olivine bands as an indication of the pyroxene-over-olivine ratio in the meteorite. The second measurement is the shift in peak position of several olivine and pyroxene spectral features since these shifts are indicative of the iron content of these silicates (Koike et al., 2003).

The paper is structured in such a way that we first introduce the measurements, sample selection and methods, followed by a presentation of the resulting spectra. Then we explain how we measure the wavelength peak positions of several olivine and pyroxene spectral features as well as the strength of several of these spectral features. This is followed by our results and we end with a discussion and conclusions.

2. Measurements

2.1. Sample selection

For this study we focussed on meteorites that represent minerals and rocks in medium to large sized planetesimals (ten to hundreds of kilometres in diameter). Measurements of carbonaceous chondrites (Beck et al., 2014) and some ordinary chondrites (OC) (Morlok et al., 2010, 2012, 2014a) have been published, but in the literature the OC and HED groups are not completely sampled and the pallasite meteorite group is not measured. These are the me-