Solid state silicate compounds are an important and abundant ingredient of matter almost everywhere in the universe, except for the hot interiors of stars. Their presence is detected by conspicuous emission or absorption phenomena observed over the whole spectrum of electromagnetic radiation from radio waves to the extreme UV. They are obviously formed in such diverse environments as outflows from stars, the atmospheres of Brown Dwarfs, disks around stars, and in the interstellar medium. Despite the enormous body of information on the nature and quantities of dust existing at various places in space derived by observations, the mechanisms responsible for its formation are still poorly understood. This contribution will discuss the present state of the theory and the key questions that still have to be solved in order to arrive at a coherent picture of silicate formation: nucleation of seed particles from the gas phase, surface growth of dust grains, what determines the iron content of the silicates, what are the conditions to form crystalline silicates? In particular recent developments based on reaction kinetics are considered. It is discussed what kind of input still has to be determined by from laboratory experiments for modelling dust formation and dusty objects, and what kind of input could be obtained by future quantum chemistry calculations.
Invited speaker:

Dust formation and processing in the ISM

Cornelia Jäger
MPIA Laboratory Astrophysics and Cluster Physics Group, Institute of Solid State Physics, FSU Jena, Germany

In the interstellar medium (ISM), amorphous silicates and carbonaceous materials that form the bulk of interstellar dust, must be the result of grain condensation and growth at low temperatures and densities in molecular clouds. This process is not yet completely understood. In our laboratory, we have designed experiments to study the cold condensation and processing of silicates in the ISM. Atoms, clusters, and molecules representing the reaction products of destructive dust processes, were deposited on substrates kept at temperatures between 6 and 20 K. These substrates simulate the cold surfaces of surviving dust grains. We have studied the co-condensation of refractory, dust-forming atoms and molecules such as Mg, Fe, oxides, and SiO molecules at low temperature. The formation of complex silicates could be observed. Our experimental results support the hypothesis that interstellar silicates are formed by accretion through barrierless reactions.
The interplay between observational, theoretical and laboratory studies of silicates

Angela Speck
University of Missouri, U.S.A.

Silicate grains dominate the emission and extinction in many astrophysical environments, and are almost ubiquitous throughout the universe. However, we still do not know exactly what constitutes these dust grains or how they change from location to location. In addition, silicate dust plays an essential role in star formation processes, and contributes to several aspects of interstellar processes such as gas heating and the formation of molecules. Moreover, since mass-loss from evolved stars is radiation driven, it is intimately linked to the precise nature of the circumstellar dust, which affects the coupling between stellar radiation and circumstellar material. Understanding the nature and formation of silicate dust is crucial to our understanding of the cosmos, yet our understanding of these dust grains is still limited by the mineralogical data used for analysis of astronomical observations. We need to know the optical properties of the many forms of silicate that exist. The laboratory study of silicates remains an essential component of studying silicates in space. This presentation, will provide historical context for the current state of studies of silicates in space, as well as showing how much progress we have made in the ~45 years since the discovery of the classic 10 micron silicate feature. We will discuss the missteps and the success and suggests ways to move forward.
Invited speaker:

Infrared spectra of silicates dust studied in the laboratory

Chiyoe Koike
Ritsumeikan University, Japan

Only amorphous silicates detected in interstellar and around circumstellar until ISO started observation, although some comets and some objects were detected crystalline silicates. ISO results showed the infrared spectra of many crystalline silicates such as olivine and pyroxene, like those of many amorphous silicates. Afterwards, Spitzer results also present further excellent spectra of crystalline silicates in many objects.

Before ISO, the lab work was chiefly how to synthesize amorphous silicates which show similar infrared spectra of interstellar. After ISO in which many crystalline silicates were detected, lab work shifted to next step, that is, how to synthesize crystalline silicates, and how the spectra depend on these properties.

The infrared spectra of crystalline silicates strongly influenced by crystallinity, chemical composition, grain morphology (size, shape, agglomeration, porosity, defects), medium (KBr, CsI, polyethylene), temperature, etc.

In this talk, I will review the infrared spectra of silicates in the laboratory, where we measured the infrared spectra of crystalline silicates such as olivine and pyroxene including amorphous silicates. Further, I will comment about the lab data.
An experimental approach to the subsolidus crystallization of the protoplanetary silicate dust

Mathieu Roskosz and Hugues Leroux
Unité Matériaux et Transformations (UMET), France

The crystallinity of silicate dust detected in protoplanetary disks contrasts with the dominantly amorphous nature of dust in the interstellar medium. The amorphous-to-crystal transition is therefore a valuable probe to constrain physical properties of disks. However, it requires a comprehensive knowledge of the behaviour of amorphous Mg silicates during thermal processing.

In this presentation, I will show experimentally that the decoupling of cation mobility in amorphous silicates always favours the crystallization of the most Mg-enriched silicates at the expense of the thermodynamically stable phase.

These results explain why below ~1000K, the mineralogy of crystalline silicate dust of solar composition should naturally be dominated by olivine while above this temperature pyroxenes should dominate. They also suggest that silica polymorphs, recently detected in cold regions of disks and in the cometary samples returned by the Stardust mission, are the natural by-products of this low temperature subsolidus solid-solid crystallization route.
Silicate dust in the far infrared and submillimeter range: observations, experiments, modelling and open questions

Karine Demyk
Institut de Recherche en Astrophysique et Planétologie (IRAP), France

Herschel and Planck have open up the far infrared (FIR) and submillimeter (submm) spectral range to detailed studies. FIR/submm observations traces the emission from cold large dust grains mainly composed of silicates, oxides and to a lesser extent to carbonaceous dust. It allows us to detect pre-stellar clouds and thus to study the very first steps of star formation but also to trace cold matter within distant galaxies. It is further used to estimate the dust mass of interstellar clouds. A good knowledge of the dust physical, chemical and optical properties, and of its thermal emission is therefore needed in order to correctly interpret observational data.

In this presentation I will expose the main results obtained from the interpretation of Herschel and Planck observations of the dust emission and discuss the difficulties and bias encountered in the interpretation of these data. I will also present the results of experimental studies carried out on silicate dust analogues to characterize and understand their spectroscopic properties in the FIR/submm range at low temperature. I will discuss the various sets of experimental data and modeling tools available for interpreting astronomical observations.
Cement nanoparticles in Space: from stars to asteroids

**Goranka Bilalbegovic**
University of Zabreb, Department of Physics, Croatia

Cement is one of the most used materials on Earth and it is modelled by calcium silicate hydrate. Using density functional theory methods we calculate infrared spectra of several Ca-Si-O-H nanoparticles. A specific calcium silicate hydrate feature at 14 microns together with typical silicate bands at 10 and 18 microns could be used for detection of cement in Space. We found 14 microns band in spectral features of several oxygen-rich circumstellar dust shells observed by ISO and classified as remaining.
Formation and evolution of micron-sized silicate grains in the dense ISM

**Jürgen Steinacker**
IPAG Grenoble, France

Our poor knowledge of the dust properties in molecular clouds dominates the uncertainties in the key physical parameters controlling the onset of star formation. Aside of extinction and thermal emission, observing scattered MIR light (so-called coreshine) has recently been added as a dust analysis tool to overcome this problem. Based on the data analysis of two dedicated large Spitzer programs we describe why the origin of large silicate grains in molecular cloud cores is currently unknown, and how we can proceed in this matter. Finally, as being relevant for the workshop topic, we will briefly sketch the status of the ongoing 3D dust radiative transfer benchmark collaboration TRUST.
Investigating dense interstellar environments in the X-rays

Sascha Zeegers, Elisa Costantini, Cor de Vries and Alexander Tielens
SRON Netherlands Institute for Space Research, The Netherlands

We present the modelling of the silicon absorption edge due to dust absorption along the line of sight of bright X-ray sources. The shape and observed energy of these edges can reveal the composition and abundance of the intervening dust grains in different environments of our Galaxy. In order to determine what type of dust best fits the observed spectra, we compared these spectra with laboratory data of different silicates that resemble the possible composition of the dust. As a test case we applied our models to a high-quality spectrum of the bright X-ray binary GX5-1, located in the vicinity of the Galactic Center.
Nucleation of SiO and Silicates from the Bottom-up

**Stefan T Bromley**, Juan Carlos Gomez Martin, John Plane
University of Barcelona, Spain

Using global optimisation we search the complex energy landscape of cluster isomers for the most energetically stable \((\text{SiO})_N\) and and magnesium silicate species. For a size range covering simple monomers to clusters with up to 40 atoms, we accurately calculate their free energies under a range of astronomically relevant conditions (e.g. circumstellar outflows, the interstellar medium) using electronic structure calculations based on density functional theory. For \((\text{SiO})_N\), the bottom-up generated free energy data is then used as input for calculating nucleation rates using a kinetic approach based on Rice-Ramsperger-Kassel-Marcus (RRKM) theory. We also compare our RRKM results with an "ab initio" Classical Nucleation Theory (CNT) approach where the free energies of our clusters are directly used as input.
Chemical formation routes towards silicate dust

David Gobrecht
OA Teramo, Italy

Although circumstellar silicate grains have been investigated and their spectral features are used to determine the chemical composition, mineralogy, size, shape, and temperature of the dust grains, its synthesis remains poorly understood.

Classical nucleation theory and thermodynamic equilibrium calculations have been used to predict the amount and composition of the dust components for oxygen-rich, S-type, and carbon-rich AGB stars (see e.g. Ferrarotti & Gail, 2006).

However, circumstellar AGB envelopes are periodically crossed by pulsational shocks and thus, an active non-equilibrium chemistry is ongoing in the post-shock gas, affecting the prevalent molecules (CO, H$_2$O, SiO, SiS, CS, HCN, SO, SO$_2$, TiO, NaCl) as well as the cluster and dust formation.

We present results on molecules, dust clusters and grains by using a chemical-kinetic reaction network coupled to a condensation routine and finally, we derive masses and grain size distributions for alumina and silicate (enstatite and forsterite) dust.

The results for the prevalent molecules, the dust-to-gas mass ratios and the dust location agree with the most recent observations, despite the model grain sizes are rather low (~ 0.04 $\mu$m).
Condensation experiments of forsterite and corundum under circumstellar conditions

Aki Takigawa and Shogo Tachibana
Kyoto University, Japan

The growth rates of circumstellar dust grains are in proportion to the condensation coefficient (a dimensionless parameter representing the degree of kinetic hindrance on condensation). Condensation experiments of forsterite and corundum were performed under protoplanetary disk-like conditions in the system of H₂-H₂O-forsterite and in vacuum, respectively. The condensation coefficients for vapor growth of forsterite and corundum were quantitatively obtained.
In-situ IR Measurement of Magnesium Bearing Silicate Nanoparticles Condensation via Homogeneous Nucleation

Shinnosuke Ishizuka, Yuki Kimura, Itsuki Sakon
Hokkaido University, Institute of Low Temperature Science, Japan

We have developed a nanoparticles condensation experimental system, in which we can measure IR evolution in-situ. We applied it to magnesium bearing silicate and succeed to reproduce broad 9.7 μm band of amorphous silicate observed around AGB stars by just condensed free-flying nanoparticles. The broad 9.7 um band was gradually changed to sharp peaks at 9.7 and 10.8 μm, which are attributed to crystalline forsterite, as nanoparticles cooled in 1 sec. Multistep process can be caused by surface instability of seed nuclei. We will give a new insight into crystalline formation at low temperature region around oxygen rich AGB stars.
Infrared spectroscopic measurements and optical constants of diopside

Harald Mutschke
AIU Jena, Germany

Diopside is a calcium magnesium silicate belonging to the clinopyroxene group. Because of its high thermal stability and its abundance in early solar-system condensates, it may be an important constituent of dusty media in certain cosmic environments. I will present and discuss powder spectra of a terrestrial diopside and related minerals, as well as optical constants derived from reflection spectroscopy of polished diopside crystal faces. Possible application to the interpretation of astronomical dust spectra will be discussed, too.
**MIR investigations of non-stoichiometric Fe-Mg silicates**

**Akemi Tamanai**, Ralf Dohmen, Hans-Peter Gail, Annemarie Pucci
Heidelberg University, KIP, Germany

One of the primary dust species in both circum- and interstellar environments is the Fe-Mg silicates. Nevertheless, formation and evolution processes of Fe-Mg silicates have not been well understood yet. We report herein the changes in the Si-O stretching (10 μm) and O-Si-O bending (20 μm) bands of the different non-stoichiometric amorphous silicates (olivine) fabricated by well-defined pulsed laser deposition (PLD) technique for a better understanding of the effect of metals (Mg & Fe) on the silicate system. The dielectric properties of the amorphous silicates derived from spectroscopic ellipsometry will be introduced as well. These experimental results may support to enhance a degree of comprehension of the nature and composition of the silicate dust in astrophysical environments.
Planetesimal formation via fluffy dust aggregates

Akimasa Kataoka, Hidekazu Tanaka, Satoshi Okuzumi, Koji Wada
University Heidelberg, ITA, Germany

Micron-sized dust grains coagulate in circumstellar disks to form planetesimals. We have included the static compression of dust aggregates to investigate the porosity evolution of dust aggregates. As a result, we found that dust grains once form fluffy dust aggregates with a filling factor of $10^{-4}$, and then they are compressed by ram pressure of the disk gas and their self-gravity to form compact planetesimals. Icy dust aggregates can avoid most of the problems of planetesimal formation such as radial drift, fragmentation, and bouncing barriers, although the fragmentation barrier is still a severe problem for silicate planetesimal formation.
Optical properties of fractal dust aggregates

Ryo Tazaki, Hidekazu Tanaka, Satoshi Okuzumi, Akimasa Kataoka, and Hideko Nomura
Kyoto University, Department of Astronomy, Japan

We investigate the absorption and scattering of lights by fractal dust aggregates in protoplanetary disks. Firstly, based on the rigorous calculation by T-Matrix Method, we show that commonly used the effective medium approximation fails to reproduce phase function by orders of magnitude at shorter wavelength domain compared to the size of the aggregates. Next, we show that the phase matrix elements (e.g., phase function, polarization) of the aggregates can be well described by using Rayleigh-Gans-Debye theory. In the talk, we also discuss the applicability of the effective medium theory and the Rayleigh-Gans-Debye theory for calculating phase matrix elements, opacity and asymmetry parameter of fractal dust aggregates.
New Constraints on the Abundance of Silicate Stardust from Supernovae in Meteorites

Peter Hoppe, Jan Leitner, János Kodolányi
Max Planck Institute for Chemistry, Germany

High-resolution (50 nm) NanoSIMS ion imaging studies of primitive Solar System material suggest that supernova grains are abundant among small (<150 nm) presolar silicate grains. The relative abundances of potential supernova grains of 33 % by number and 20 % by mass inferred from high-resolution ion imaging are clearly higher than the 10 % by number previously found from lower resolution (100 nm) ion imaging studies and the 5 % by mass estimated by a model for stellar dust in the ISM.
Interstellar silicate particles measured by Cassini's Cosmic Dust Analyser at Saturn

Heidelberg University, GEOW, Germany

We detected contemporary interstellar dust using the Cosmic Dust Analyser (CDA) on-board the CASSINI spacecraft. For 36 detected interstellar dust grains, flux and mass distribution and the elemental composition of each individual grain was inferred. Mass spectra suggest a relatively homogeneous population of Mg-rich silicate grains, probably with iron inclusions, with an average of cosmic (i.e. close to solar and CI chondritic) abundance ratios of Mg, Si, Ca, and Fe. Ca and S-rich grins were not detected.

As compositional variation is significantly smaller than expected for circumstellar dust grain populations (found by isotopic anomalies in meteorites), we conclude that our measurements represent a homogenised grain population, most likely by repeated processing such as shock destruction and recondensation in cold molecular clouds.
Harsh lives of massive AGB stars in star clusters

Svitlana Zhukovska
Max Planck Institute for Astrophysics, Germany

Models of dust condensation in stellar winds predict that the silicate grains from massive AGB stars should be an abundant component of the presolar grains, but no such grains have been identified so far. We examine the fraction of massive AGB stars remaining bound in their parent star clusters and the impact of irradiation of CSE of these stars by intracluster ultraviolet (UV) field. We employ a set of N-body models of dynamical evolution of star clusters rotating in the local Galaxy. We find that about 70 % of massive AGB stars evolves in star clusters, where the intracluster UV field is in many cases sufficiently strong to photodissociate SiO molecules as deep as the dust formation zone.
Dust Radiative Transfer in Star-Forming Filaments

**Roxana-Adela Chira**, Ralf Siebenmorgen, Thomas Henning
ESO, Germany

Dust emission surveys at sub-mm and far-infrared wavelengths, e.g. by Herschel, provide new possibilities to study star formation in filamentary molecular clouds.

The column density and temperature profiles that are derived with these observations have shown astronomers new details about the structure and star-formation potential of those objects.

Doing so, we need to presume in the first place that the filaments we see are inclined in such a way that we see their long axis within the plane-of-sky since dust lacks any information of the kinematics.

But how would those filaments look like if we observe them from another direction?

We apply our three-dimensional dust radiative transfer code on models of clumpy filaments at different line-of-sight angles, predict the distributions of observable quantities and discuss the results in context of observational routines.
Witnessing the emergence of a carbon star


During the late stages of their evolution, Sun-like stars bring products of nuclear burning to the surface. Using the FORCAST instrument on board the SOFIA Telescope, we obtained images of the carbon-rich planetary nebula BD +30 3639 which trace both carbon-rich PAHs and oxygen-rich silicate dust. With the superior spectral coverage of SOFIA, we prove that the O-rich material is distributed in a shell in the outer parts of the nebula, while the C-rich material is located in the inner parts of the nebula. These observations combined with a 3D radiative transfer model, suggest a recent change in stellar surface composition for the double chemistry in this object. This is evidence for dredge-up occurring a few 1000 yr ago.
The Rosetta lander Philae successfully landed on the nucleus of comet 67P/Churyumov-Gerasimenko on 12 November 2014 at a heliocentric distance of 2.99 AU. Philae carries the Dust Impact Monitor (DIM) on board, which is part of the Surface Electric Sounding and Acoustic Monitoring Experiment (SESAME). DIM employs piezoelectric PZT sensors to detect impacts by sub-millimeter and millimeter-sized ice and dust particles that are emitted from the nucleus and transported into the cometary coma. The sensor measures dynamical data like flux and the directionality of the impacting particles. Mass and speed of the grains can be constrained for pre-defined density and elastic grain properties. During Philae’s descent to its nominal landing site Agilkia, DIM detected one approximately millimeter-sized particle at an altitude of 2.4 km from the nucleus surface. This is the closest ever dust detection at a cometary nucleus by a dedicated in-situ dust detector. The material properties of the detected particle are compatible with a porous grain having a bulk density of approximately 250 kg m$^{-3}$. At Philae’s final landing site, Abydos, DIM detected no dust impact which may be due to low cometary activity in the vicinity of Philae at the time of landing, or due to shading by obstacles close to Philae, or both. We discuss the DIM measurements at comet 67P and compare our results with data obtained by other Rosetta dust instruments.
Rates and mechanisms of diffusion and diffusion controlled reactions in silicates

Ralf Dohmen
Ruhr-University Bochum, GMG, Germany

Knowledge of diffusion rates in crystalline and amorphous silicates is a fundamental prerequisite to model post modification of silicate dust in different interstellar environments. Recent experimental advances by using thin film technology and nanometer-scale analytical methods have helped to increase significantly the available database for diffusion coefficients and new experimental approaches were developed to investigate solid-state reactions. An overview will be given on the measured diffusion coefficients of major cat- and anions in spinel, olivine, ortho- and clinopyroxene, but also silicate glasses. Recent data for Fe-Mg interdiffusion in silicate minerals were measured down to 700 °C constraining the diffusion behavior at relatively low temperatures. In addition rates of solid state reactions, like those of the formation of enstatite from olivine and quartz will be discussed.