Insight into planetary growth:

Influence of high temperatures on chondritic material

Cynthia Pillich[1], Tabea Bogdan[1], Joachim Landers[1], Gerhard Wurm[1] and Heiko Wende[1]

[1]Faculty of Physics, University Duisburg-Essen, 47057 Duisburg, Germany

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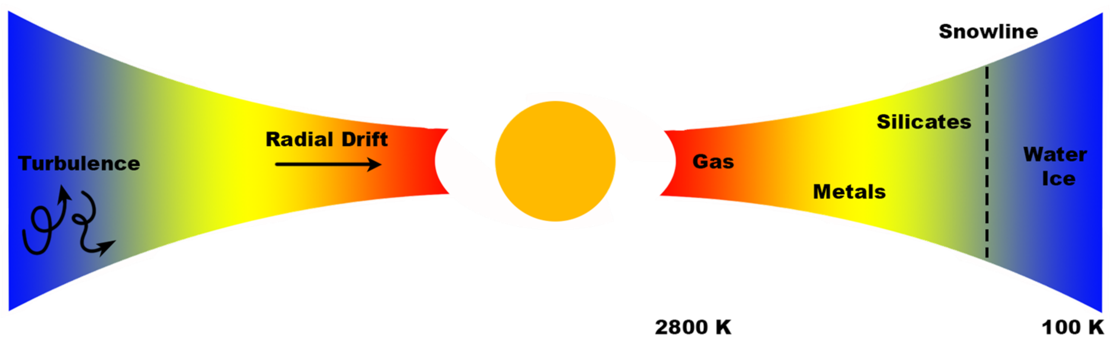
Motivation

- **Protoplanetary disks** around young stars hold material for planetary formation
- Planetesimal formation starts with **micrometer sized dust grains**, colliding and sticking to each other [1,2]
- Growth of planetesimals dependent on **cohesion**, **turbulence** [3] and **bouncing** [4]



[5]

How does temperature in protoplanetary disks influence these processes?

- Heating particles inside the disk can lead to changes in morphology and chemical composition
- This can lead to **altered sticking parameters**
- Are there favored areas for planetary growth?

Meteorite Sayh al Uhaymir (SAU001)

[6]

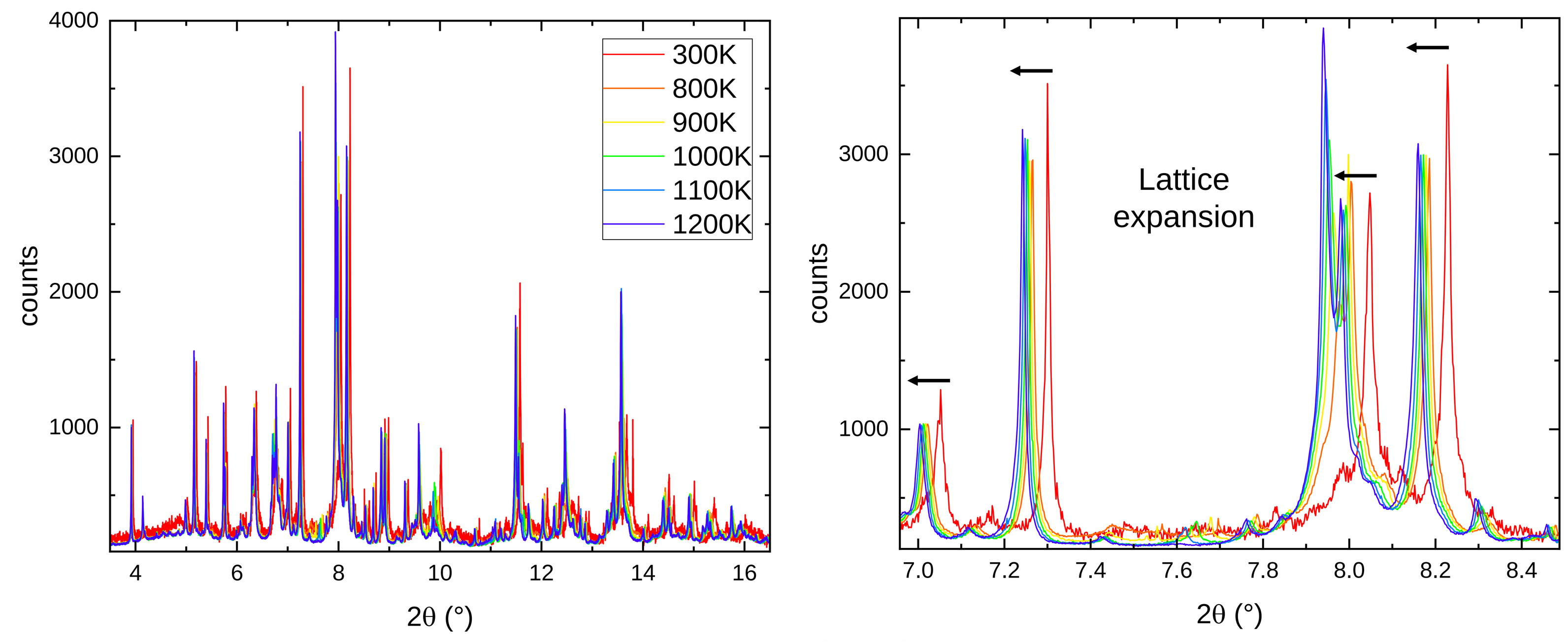
- **Chondrites** composed of chondrules, contain primordial phases representing material found in our young solar system.

Laboratory study of chondritic material to gain information on planetesimal formation

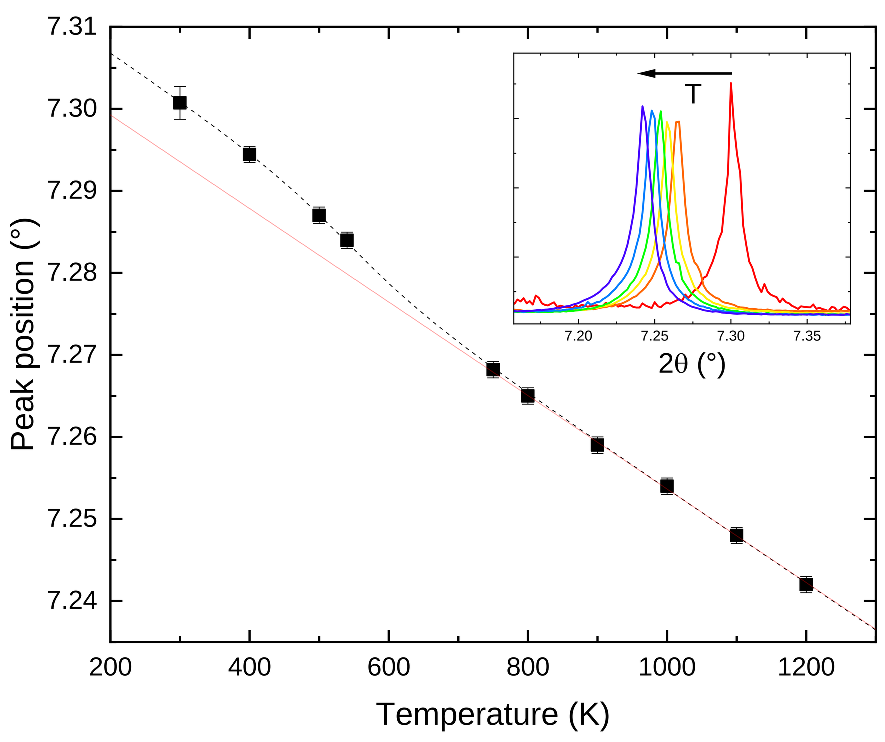
- SAU001 undifferentiated, ordinary chondrite of class L4/5 (low in iron, only slightly altered thermally)
- ^{57}Fe Mössbauer spectroscopy and in situ synchrotron XRD to determine effect of high temperatures on the properties of SAU001

Dynamic thermal processes in SAU001

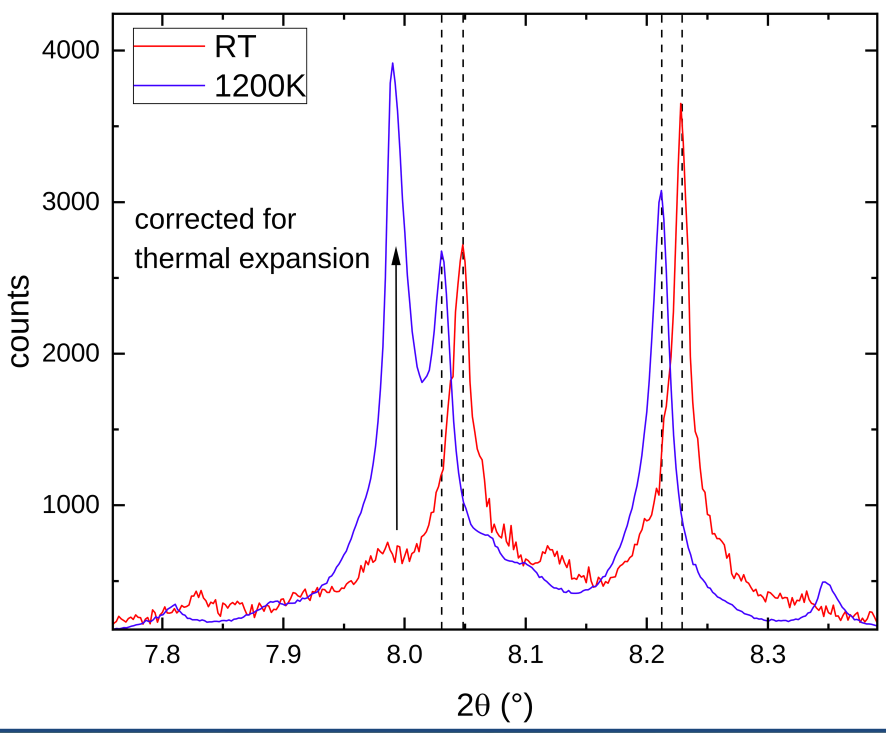
- **In situ synchrotron XRD** used to study dynamics while heating chondritic material
- Diffractograms measured at **ID22 at ESRF** in Grenoble, France



- Variety of overlapping peaks, mostly olivines ($(Mg^{2+},Fe^{2+})_2SiO_4$), but also pyroxenes ($(Mg^{2+},Fe^{2+})Si_2O_6$ and iron oxides
- **Thermal expansion** shifts reflexes to lower angles
- Also **compositional changes** can lead to a shift to lower or higher reflection angles

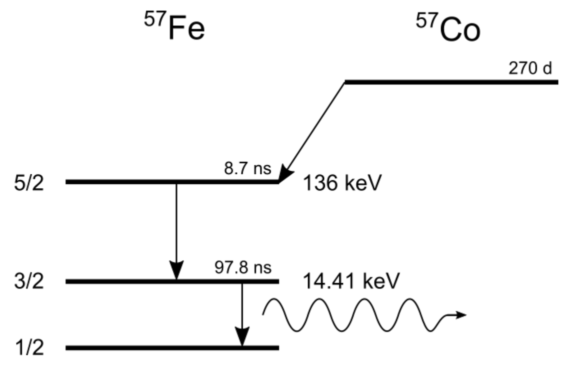


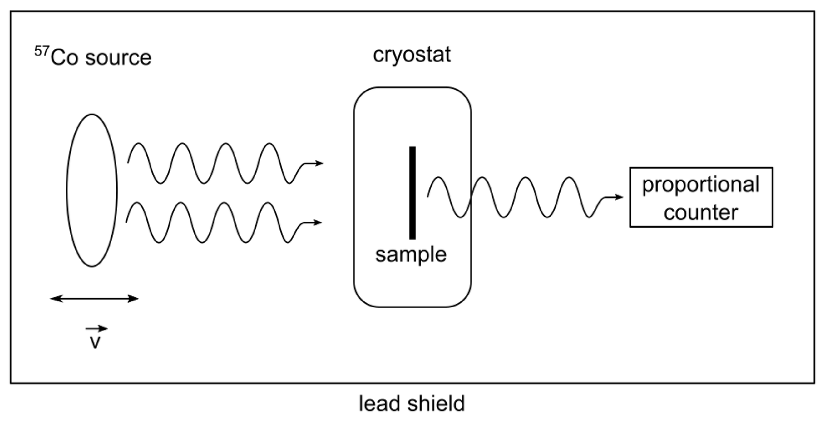
- Studies on chondritic meteorite with similar chemical composition (Allende) show linear thermal shift between 300 – 1200K
- Peak positions of the main peaks show a different behaviour for SAU001
- With rising temperatures, position of the mineral's reflex (in this case $Mg_{1.4}Fe_{0.6}SiO_4$) overall decreases
- Declining trend can best be described by a sigmoid function with a broad decreasing step at ~550K
- This could be an indication for **phase transformation happening in this temperature range**, resulting in an increase of iron content in olivines and therefore an increase in their lattice constants



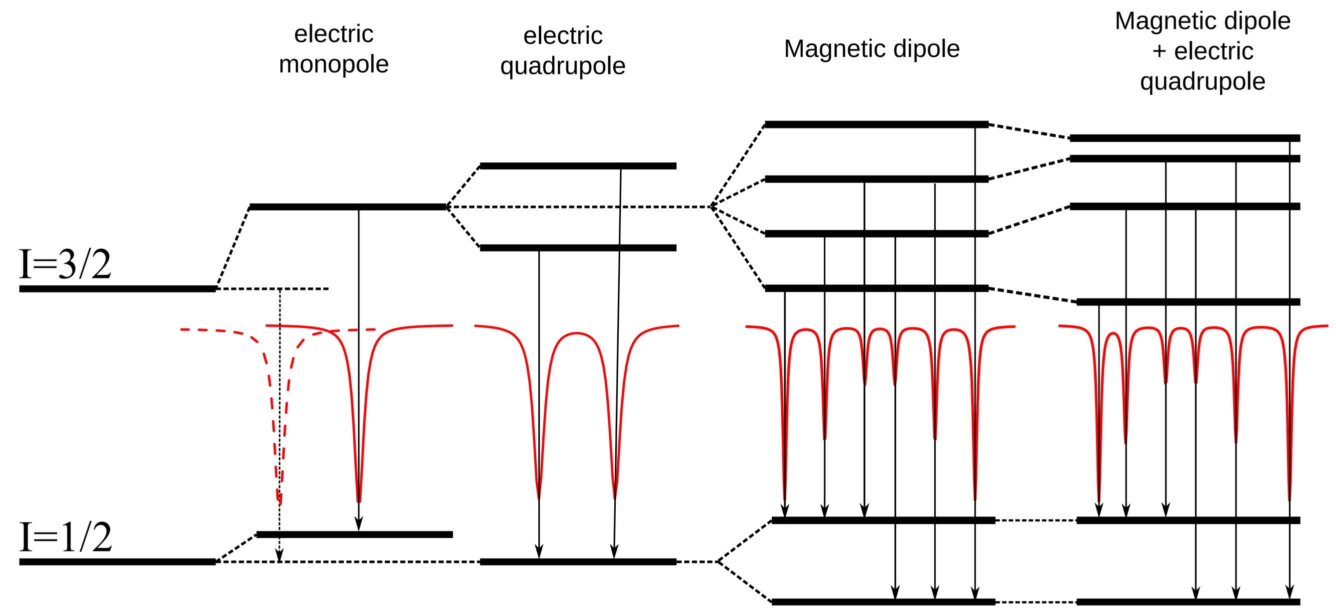
- Correct diffractograms of SAU001 for thermal expansion
- Still noticeable shift of ~0.017° to lower angles for the powder heated at 1200K
- Red peaks show lattice reflexes of iron poor olivine $Mg_{1.4}Fe_{0.6}SiO_4$
- Lattice constant of olivines increases approx. linearly with iron content [8], tempering seems to lead to an **enrichment with iron (from ~30% to ~40% iron)**
- Sharp rise in signal at ~8° after heating over 800K, likely induced by **olivines with iron content of 50 – 70%**

^{57}Fe Mössbauer spectroscopy



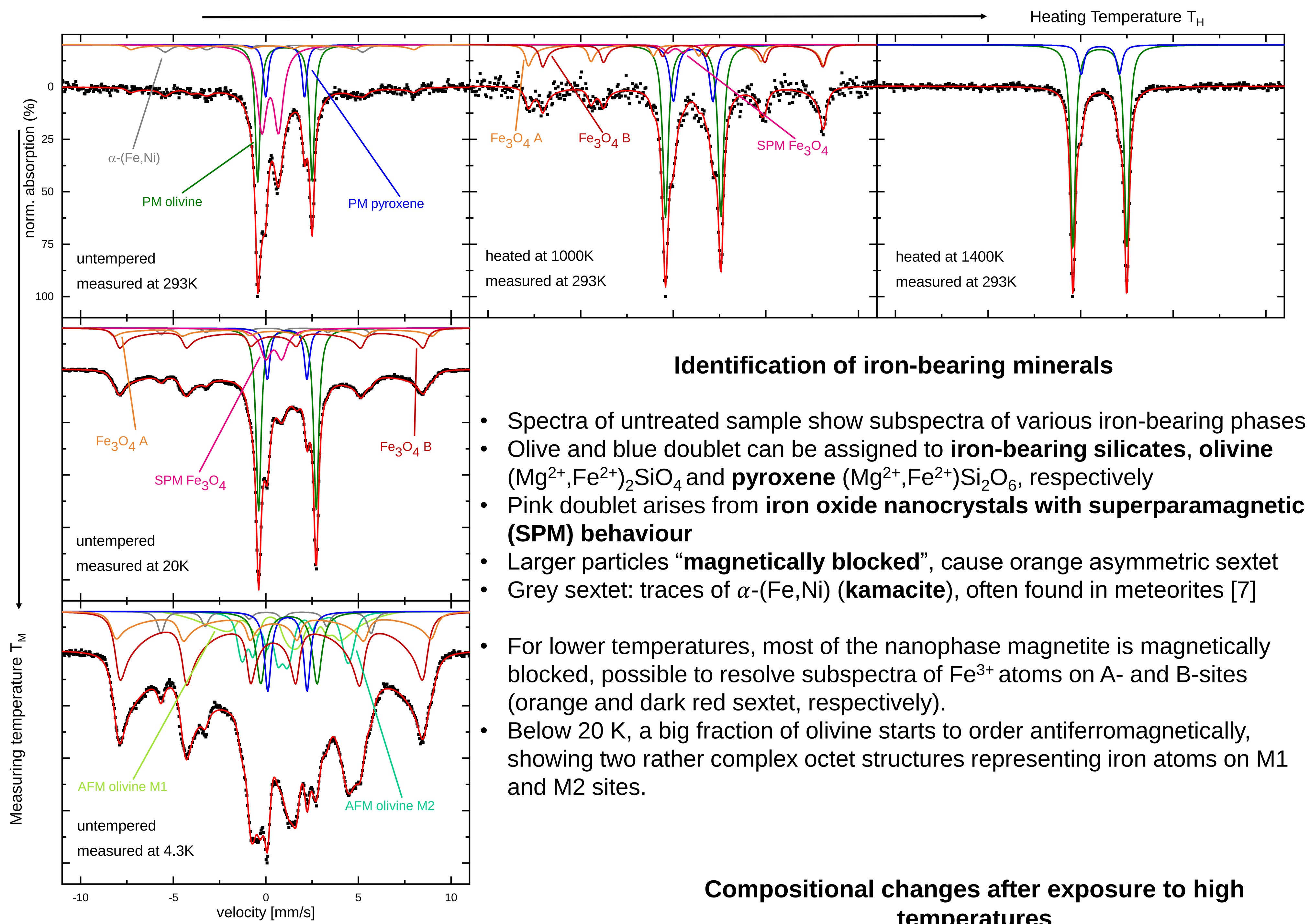


- **^{57}Fe Mössbauer spectroscopy** to analyze electric and magnetic interactions in **iron-bearing minerals**
- Transition from nuclear excited $I_{3/2}$ to ground state $I_{1/2}$ leads to emission of **γ-quanta $E_\gamma = 14.4\ keV$, sharp linewidth $\Gamma = 5\ neV$**
- Energy of absorption line can be modified by use of Doppler-effect



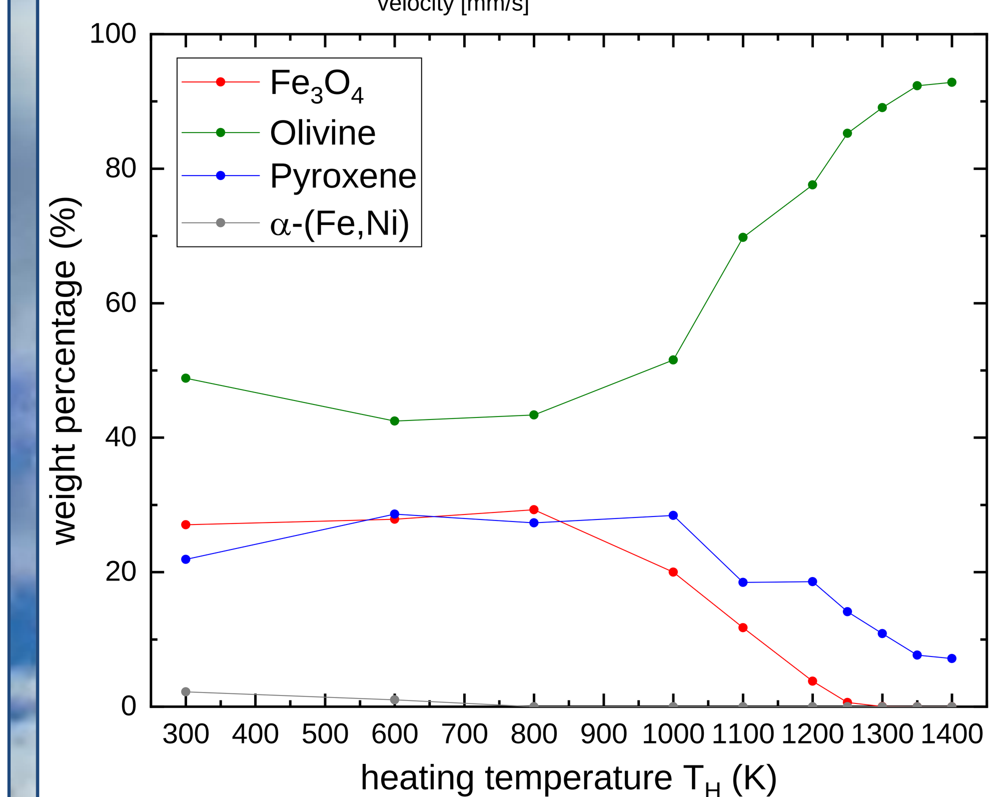
- Hyperfine interactions of ^{57}Fe nucleus with electronic surrounding modify absorption line
- Electric monopole interaction → **Isomer shift δ** sensitive to valence state of absorbing iron atom
- Interaction of nuclear quadrupole moment with electrical field gradient → **Quadrupole splitting ΔE_Q** gives information about local symmetry
- **Magnetically ordered samples** → sextet

Composition of SAU001 via Mössbauer spectroscopy



Identification of iron-bearing minerals

- Spectra of untreated sample show subspectra of various iron-bearing phases
- Olive and blue doublet can be assigned to **iron-bearing silicates**, **olivine** $(Mg^{2+},Fe^{2+})_2SiO_4$ and **pyroxene** $(Mg^{2+},Fe^{2+})Si_2O_6$, respectively
- Pink doublet arises from **iron oxide nanocrystals with superparamagnetic (SPM) behaviour**
- Larger particles "**magnetically blocked**", cause orange asymmetric sextet
- Grey sextet: traces of α-(Fe,Ni) (**kamacite**), often found in meteorites [7]
- For lower temperatures, most of the nanophase magnetite is magnetically blocked, possible to resolve subspectra of Fe^{3+} atoms on A- and B-sites (orange and dark red sextet, respectively).
- Below 20 K, a big fraction of olivine starts to order antiferromagnetically, showing two rather complex octet structures representing iron atoms on M1 and M2 sites.



Compositional changes after exposure to high temperatures

- Sample was subsequently heated in vacuum for 1h at temperatures between 600 and 1400 K
- Already at moderate temperatures **compositional changes**
- After an exposure to **T_H = 800 K no kamacite** can be found in the sample anymore
- For higher temperatures, relative spectral area of nanophase magnetite decreases, **no Fe_3O_4 after heating at 1300 K**
- Relative spectral areas can be converted into weight percentages and into **density of solids** of chondritic dust
- Temperature dependent density ρ_{Dust} used to correct **sticking properties** of heated dust gathered by **Brazilian tests** [9]
- Effective surface energy γ_e of chondritic material monotonously **decreases by a factor of 5** after tempering at very high temperatures

References

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Contact: cynthia.pillich@uni-due.de

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Conclusion and outlook

- **Chondritic material** represents the chemical composition of our young solar system, rendering it interesting for laboratory studies on planetesimal growth.
- **^{57}Fe Mössbauer spectroscopy and synchrotron XRD** is a powerful combination to investigate the composition of meteorites and the influence of high temperatures on their properties
- Chondritic dust consists of mostly **olivines, pyroxenes and iron oxides**. After tempering at very high temperatures, its composition is dominated by iron bearing silicates. XRD patterns indicate an **enrichment of olivines with iron**.
- Measurements show a **significant decrease in surface energy with tempering**, influencing the potential for planetary growth in the inner protoplanetary disk, which could be related to structural and compositional changes observed in this work