



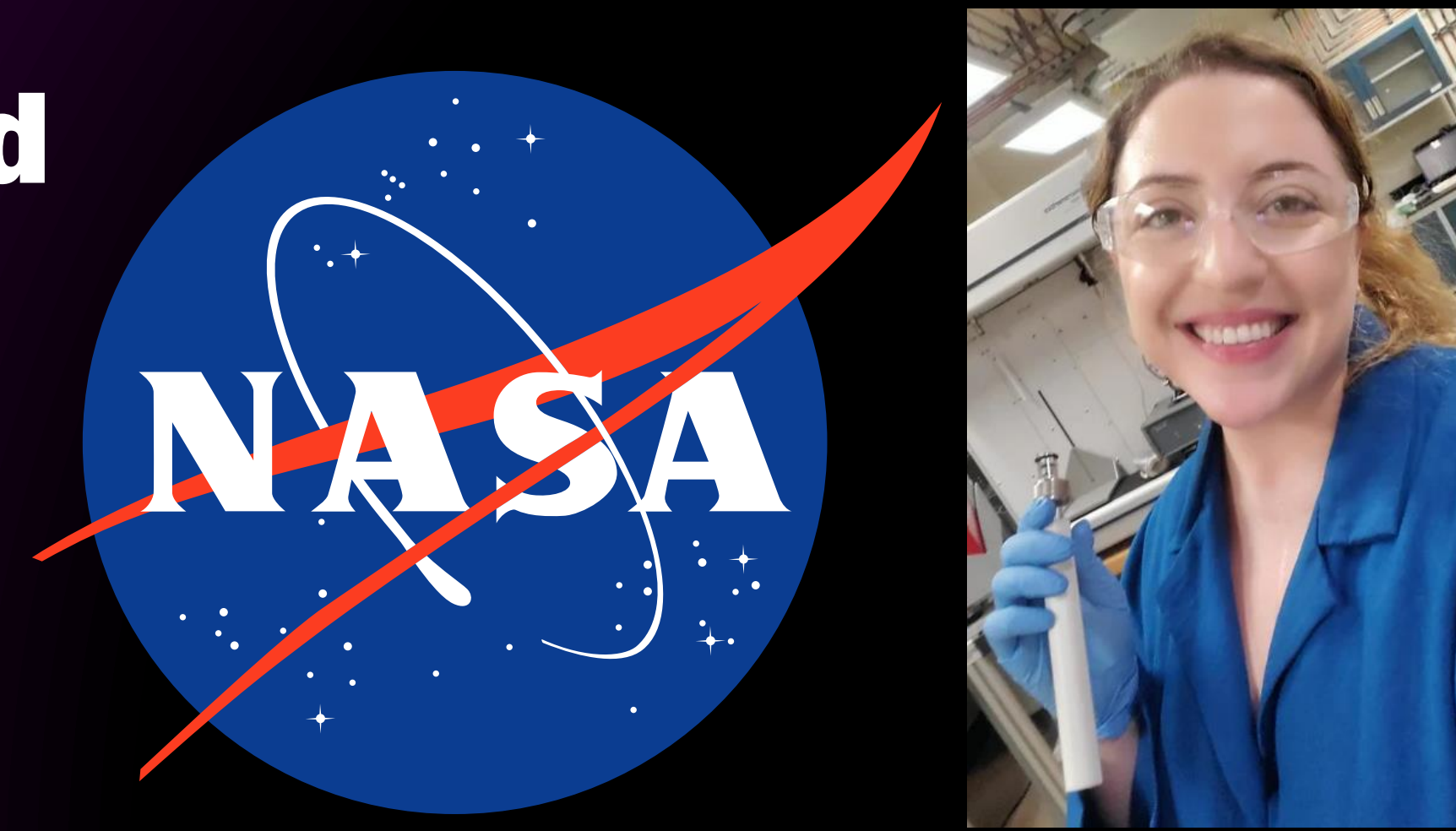
Surface Energy Measurements of Silicates with Application to Nucleation and Condensation in Exoplanet Atmospheres WASP-17b and VHS 1256b

Megan Householder^{1,3}, James Lyons², Alexandra Navrotsky^{1,3}, Tamil Subramani³, Kristina Lilova³

¹ School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287

² Planetary Science Institute, Tucson, AZ, 85719

³ School of Molecular Sciences and Center for Materials of the Universe, Arizona State University, Tempe, AZ, 85281



megan.householder@asu.edu

Abstract

Surface energies are measured using oxide melt solution calorimetry of materials with different surface areas for several likely exoplanet condensates including forsterite (Mg_2SiO_4), and enstatite (MgSiO_3), SiO_2 and amorphous silicates. The exoplanet community currently relies on theoretical or estimated surface energy data for nucleation rate calculations for hot Jupiter cloud species, which are the basis for determining which species should dominate exoplanet atmospheres. This work inputs the newly measured surface energy data to calculate nucleation rates for each of the proposed cloud species in specific planetary atmospheres such as WASP 17-b and VHS 1256b.

Motivation

The exoplanet community currently relies on theoretical or estimated surface energy data for nucleation rate calculations for hot Jupiter cloud species, which are the basis for determining which species should dominate exoplanet atmospheres. This work inputs the newly measured surface energy data to calculate nucleation rates for each of the proposed cloud species given current measured surface energies and such forsterite (Mg_2SiO_4), zinc sulfide (ZnS), enstatite (MgSiO_3), with others planned.

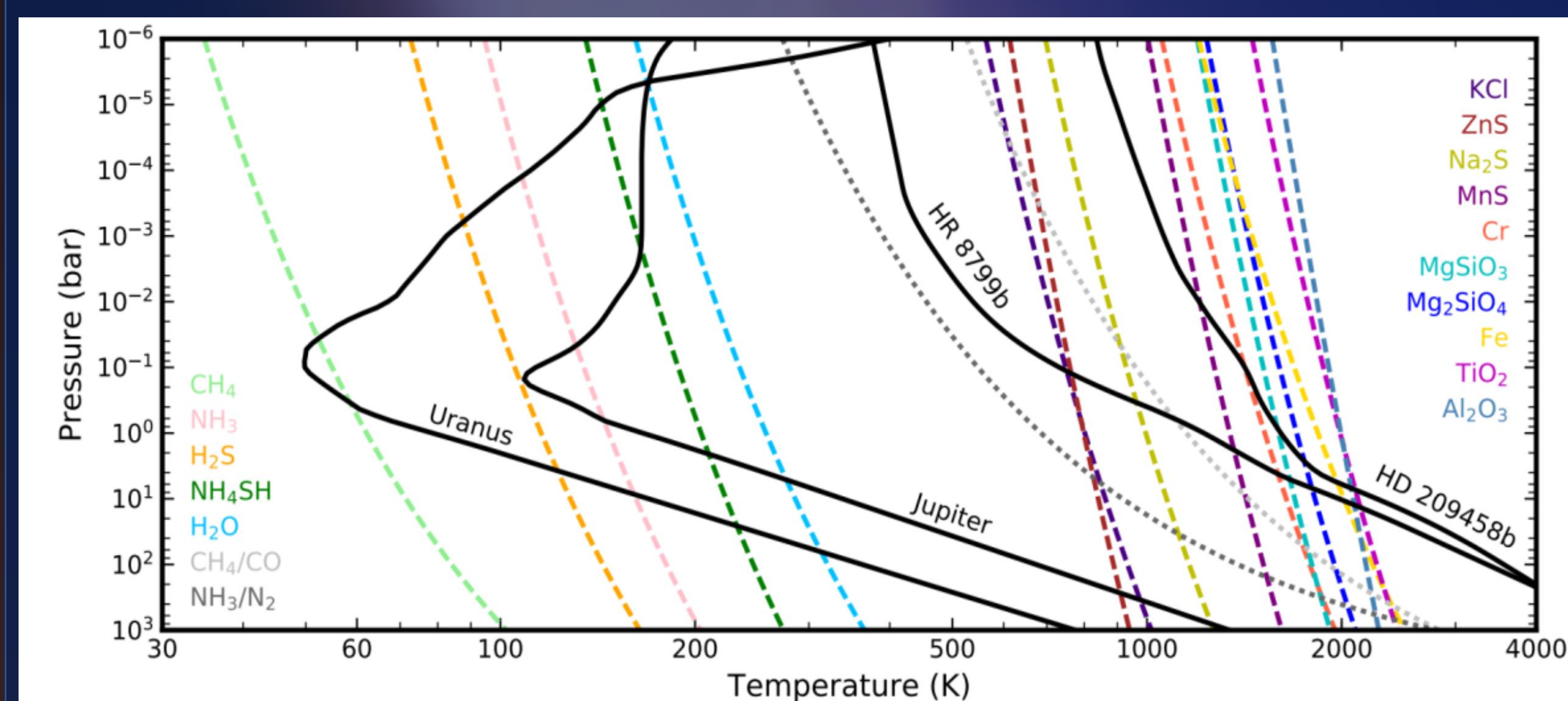


Figure 1. Dashed lines represent the condensation temperatures of several chemical species as a function of pressure. The black lines represent temperature-pressure profiles of Jupiter and Uranus and two exoplanets, HR 8799b (a young, directly imaged exoplanet) and HD 209458b (a hot Jupiter). Condensation of a given species occurs when a planet's temperature-pressure profile becomes lower than a species' condensation temperature profile. (Figure adapted from Gao et al. 2021a)

When modeling aerosol formation in hot Jupiter atmospheres, the surface energies that have been used for many condensates are close to an order of magnitude smaller than experimentally measured values using calorimetry and other methods (Table 1) (Boni & Derge 1956; Castro et al. 2006). Historically, astrophysicists have relied on atomistic estimates of surface energies, but we argue here that it is time to start using experimentally determined values.

Condensate Species	Surface energy from experimental data (erg cm ⁻²)	Surface Energy used in Exoplanet Atmosphere Literature (erg cm ⁻²)
Corundum Al_2O_3	2040 (anhydrous) ¹	690 (model) ⁵ via 6 via 7
Rutile TiO_2 (CCN)	2060 ± 100 (anhydrous) ²	425-508 (model) ⁵ via 8 via 9
Forsterite Mg_2SiO_4	4410 ± 210 (anhydrous) ³	436 (model) ⁵ via 6 via 7
Enstatite MgSiO_3	TBD	N/A
ZnS zinc sulfide	1760 (anhydrous) ⁴	860 (est.) ⁵ via 10
MnS manganese sulfide	TBD	2326 (est.) ⁵ via 11
Na ₂ S sodium sulfide	TBD	1033 (est.) ⁵ via 11

Table 1. Surface energies of potential condensate particles in exoplanet atmospheres. Blue is the measured value from a paper that has been accepted in *Geochimica et Cosmochimica Acta*, ⁴(Subramani et al. 2022), ¹(McHale et al. 1997), ²(Castro et al. 2006), ³(Chen & Navrotsky 2010), ⁵(Gao et al. 2020), ⁶(Kozasa et al. 1989), ⁷(Boni & Derge 1956), ⁸(Lee et al. 2018), ⁹(Lee et al. 2015), ¹⁰(Celikkaya & Akinc 1990), ¹¹(Zhang et al. 2003)

Material	Surface energy of crystalline species (J/m ²)	Surface energy of amorphous species (J/m ²)
MgSiO ₃ (enstatite)	4.79 ± 0.45 †	1.8 ± 0.10 §
Mg ₂ SiO ₄ (forsterite)	4.41 ± 0.21 #	1.657 **
Fe ₂ SiO ₄ (fayalite)	2.47 ± 0.20 ‡	0.93 **
SiO ₂ (silica)	1.00 ± 0.07 *	0.26 *

† (Householder et al. 2023)
§ (Householder et al. submitted)
(Chen & Navrotsky 2010b)
‡ (Lilova et al. 2018)
* (Chiang et al. 1996)
* (Parks 1990)
**Am/Cry SE ratio of 0.3758 for enstatite was used to extrapolate the amorphous forsterite and fayalite surface energies.

Table 2. Surface energies of anhydrous crystalline and amorphous silicate condensates. Green is measured value for anhydrous crystalline enstatite. Blue is measured surface energy of amorphous enstatite.

Measuring Surface Energies

$$\text{Surface energy} = \frac{\Delta H_{\text{ds}}(\text{bulk}) - \Delta H_{\text{ds}}(\text{nano})(\text{kJ/mol})}{\text{surface area (m}^2/\text{mol)}}$$

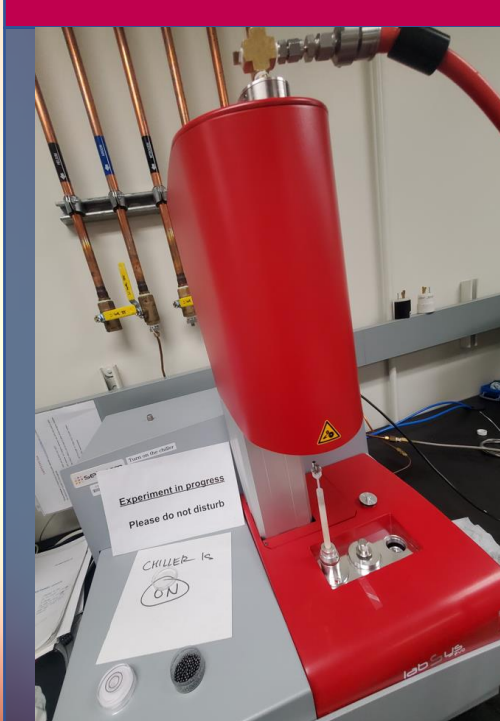
ΔH_{ds} = drop solution enthalpy

Nanoparticle Synthesis

Each chemical species has a different synthesis method. For ZnS, nano-sphalerite was synthesized using the hydrothermal method. Nano-enstatite was synthesized using the sol-gel method.



Nanoparticle Characterization



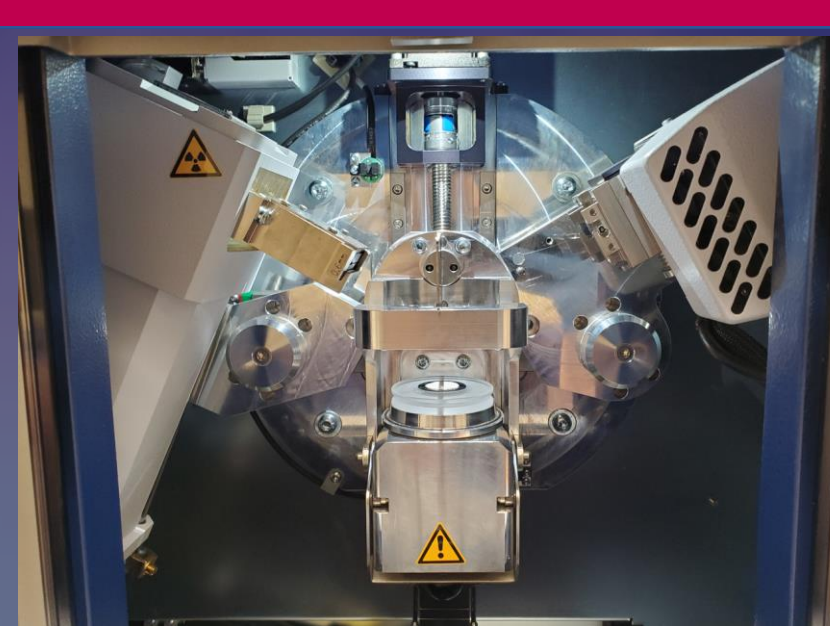
Thermogravimetry and Differential Scanning Calorimetry (TG – DSC): Setaram Labsys Evo



Scanning Electron Microscopy, Scanning Transmission Electron Microscopy, Transmission Electron Microscopy



FTIR Spectroscopy: Bruker Vertex 70 spectrometer



Powder X-Ray Diffraction (PXRD): Bruker D2 bench top diffractometer



Brunnauer-Emmet-Teller (BET) Measurements: N₂ adsorption to measure the surface area of the nanoparticles - measured at 77 K using a 10-point BET technique on the analysis port of a Micromeritics ASAP 2020

Oxide Melt Solution Calorimetry

High temperature oxide melt solution calorimetry is performed using a Tian-Calvet twin calorimeter AlexSYS at 1073 K in a sodium molybdate or lead borate solvent. The bulk and nano samples of the species are methodically dropped into the solvent to obtain the drop solution enthalpy, ΔH_{ds} . The nano sample are water-corrected for in the thermochemical cycles. The surface energy is then given by $\Delta H_{\text{ds}}(\text{bulk}) - \Delta H_{\text{ds}}(\text{nano water corrected})(\text{kJ/mol}) / \text{surface area (m}^2/\text{mol)}$.



Results

Zinc Sulfide

Until our measurements it was assumed that sphalerite was the dominant zinc sulfide polymorph in hot exoplanet atmospheres (Kopparapu et al., 2018; Gao and Benneke, 2018), but our work suggests that the formation process follows a path shown in Figure 2. ZnS precipitating rapidly from a gas phase in a planetary atmosphere (or elsewhere) is likely to form initially as a poorly crystalline or amorphous nanophas, and as the cloud condensation nucleus grows, that phase transforms to fine nanocrystalline wurtzite, followed by nano and bulk sphalerite due to coarsening, and then the condensate would transform to bulk wurtzite given a high enough temperature.

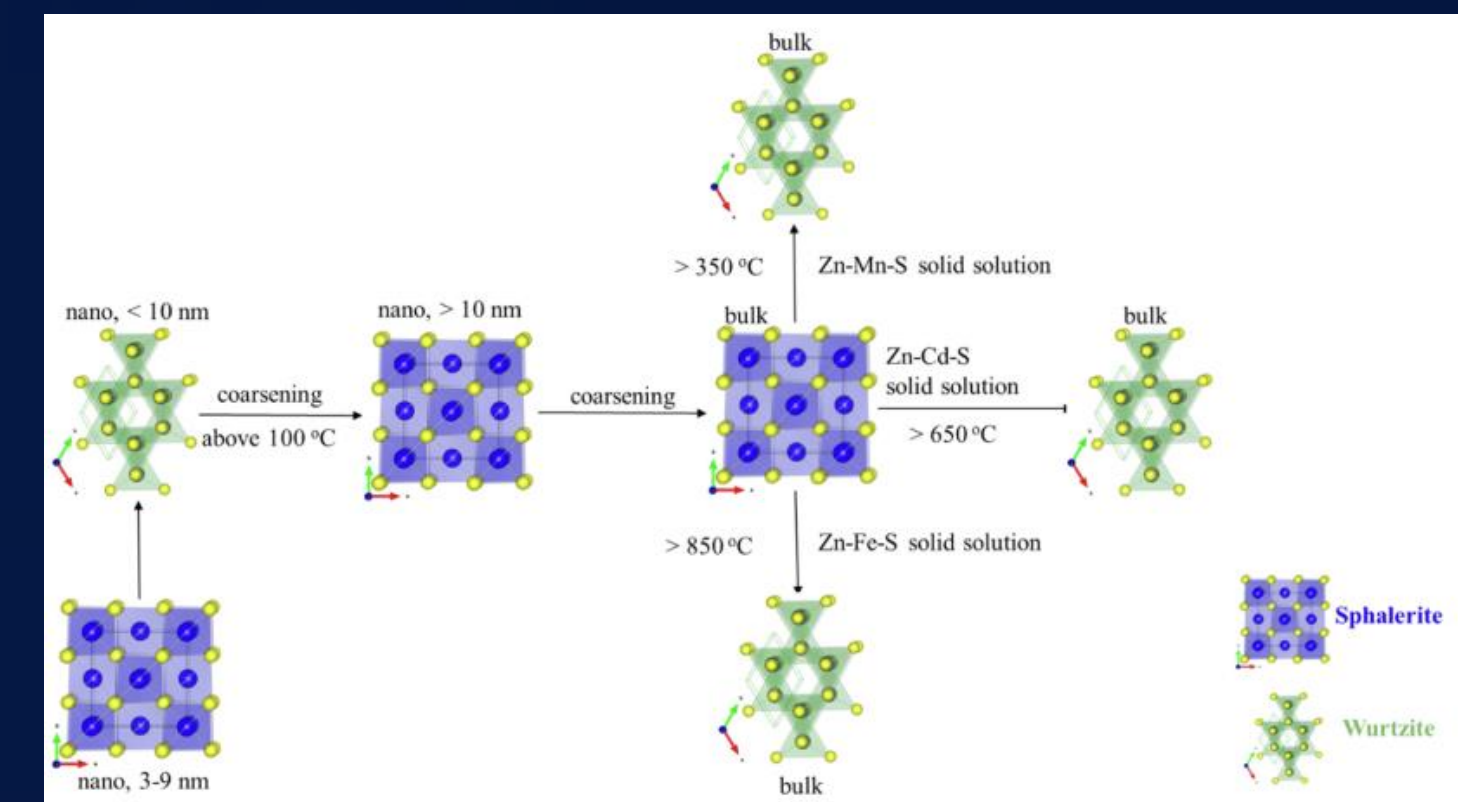
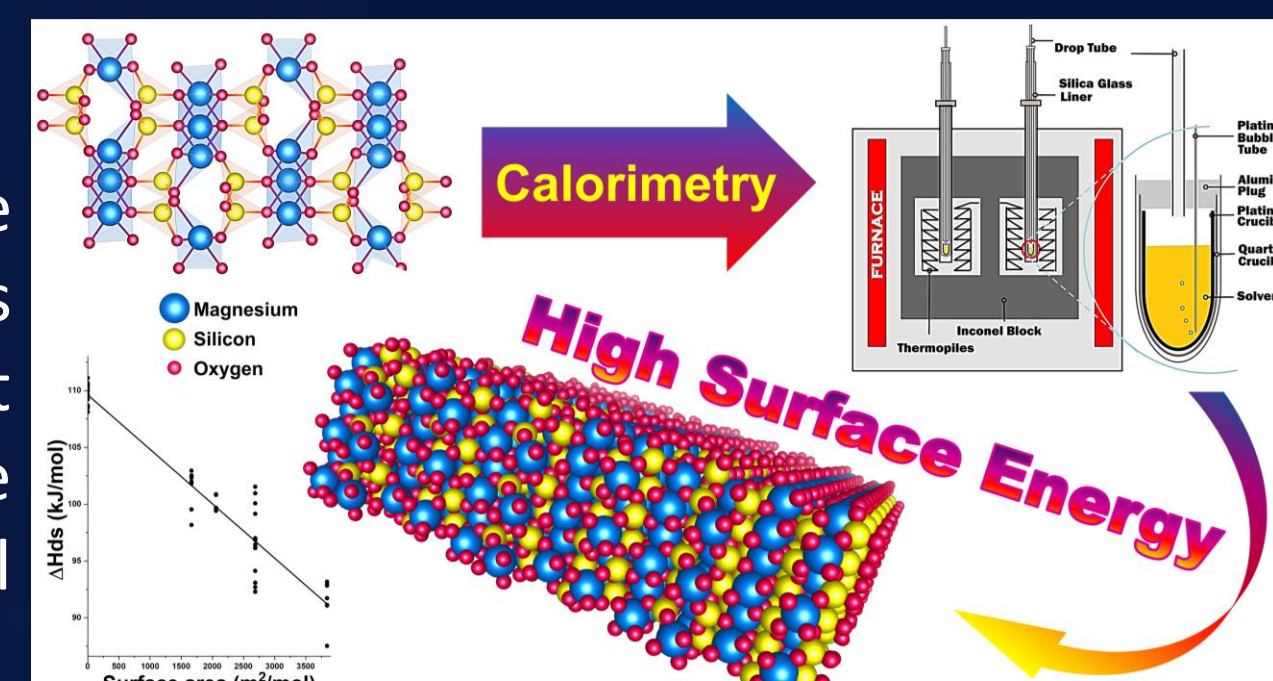


Figure 2. Formation of polymorphs from nanosized sphalerite and wurtzite in the presence of impurities

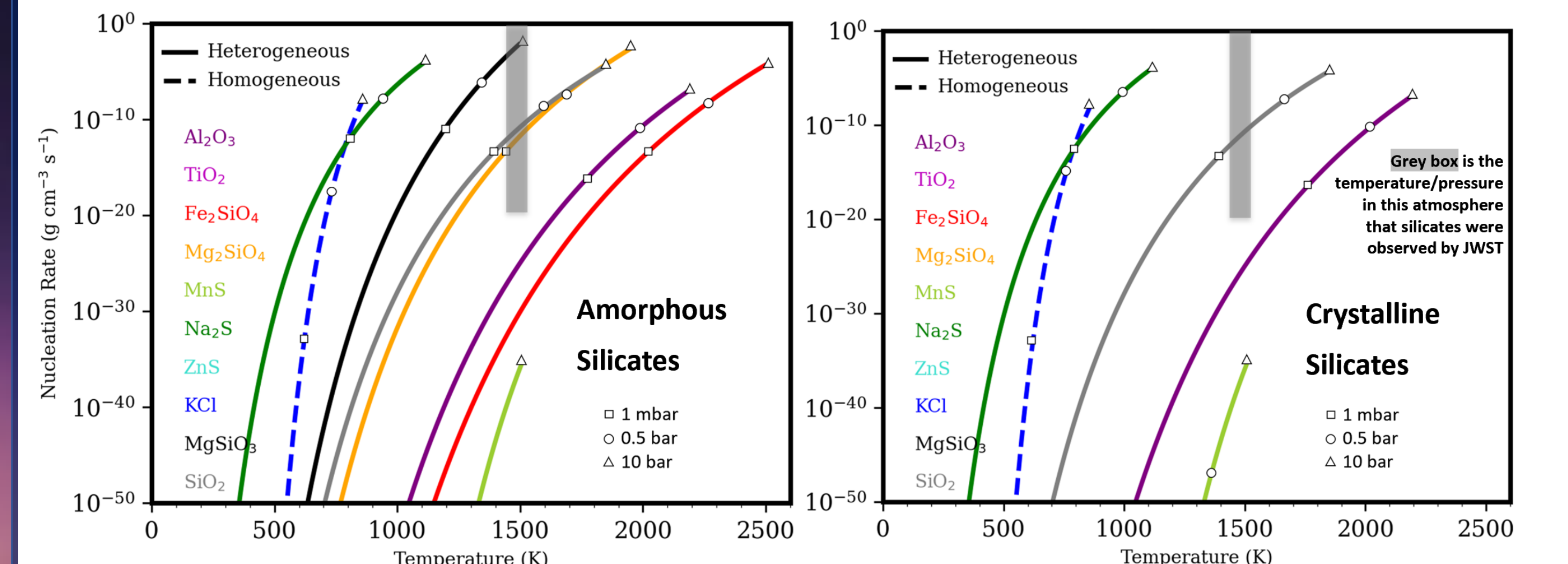
Enstatite

The newly measured surface energy of enstatite (Householder et al. 2023) The high surface energies of enstatite and forsterite likely inhibit direct condensation of crystalline nanoparticles of these two key silicates in a wide range of astrochemical environments.



Silicate Nucleation Results

Nucleation Code Results for VHS 1256b

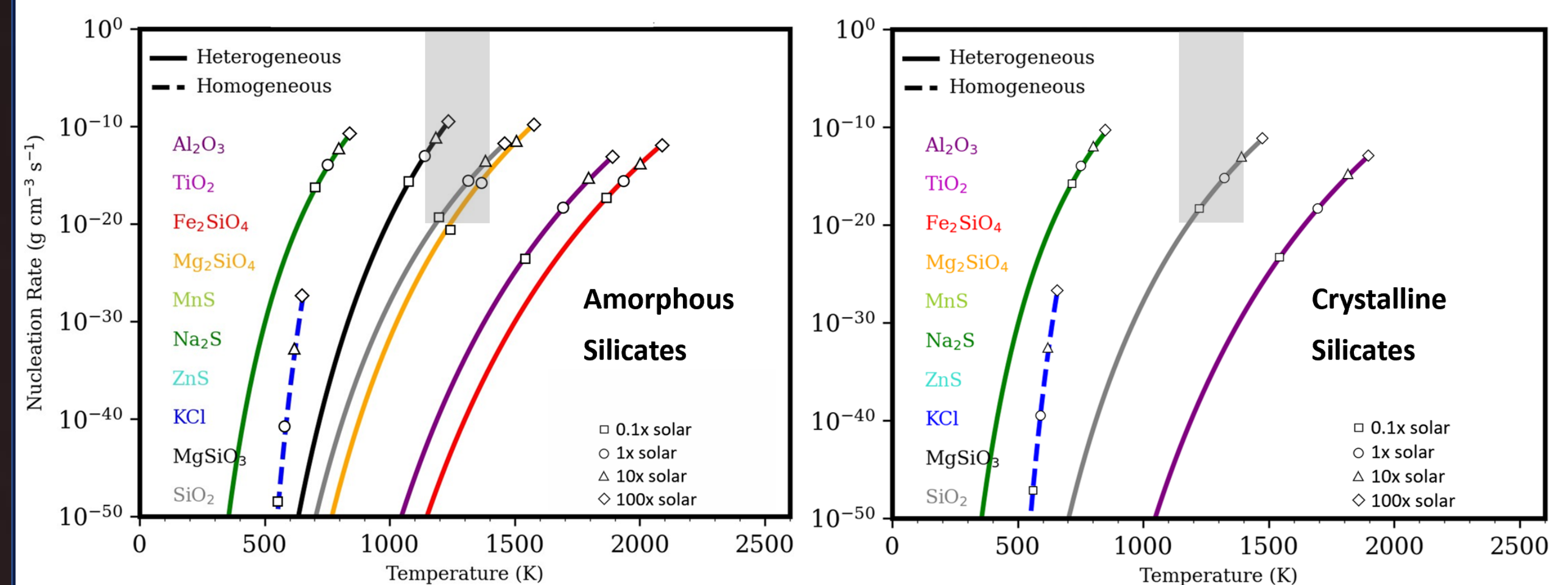


Results of the public nucleation code provided by Gao et al. (2018) for select cloud species of a hot giant exoplanet with 1x solar metallicity

Enstatite, quartz and forsterite dominate nucleation at the equilibrium temperature if they INITIALLY nucleate as amorphous

Nucleation rates as a function of temperature for select cloud species for an atmosphere analogous to VHS 1256 b with varying atmospheric pressures of 1 mbar, 0.5 bar and 10 bar with 1x atmospheric solar metallicity. The grey rectangle encompasses the temperatures at which the JWST observed silicates in VHS 1256 b. (left) Nucleation rates using surface energies for select amorphous silicate cloud species. (right) Nucleation rates using surface energies for select crystalline silicate cloud species.

Nucleation Code Results for WASP 17-b



Amorphous species nucleation rates as a function of temperature for a hot exoplanet at atmospheric pressure of 0.1 mbar with varying solar metallicities

At 0.1 mbar there may not be enough material for condensation of Mg-rich silicates

Nucleation rates as a function of temperature for select cloud species in a hot Jupiter atmosphere analogous to WASP-17b, with varying atmospheric solar metallicities of 0.1, 1.0, 10, and 100x solar and total atmospheric pressure of 0.1 mbar. The grey rectangle encompasses the temperatures at which the JWST observed SiO₂ in WASP-17b. (left) Nucleation rates using surface energies for select amorphous silicate cloud species. (right) Nucleation rates using surface energies for select crystalline silicate cloud species.

Acknowledgments

We thank Peter Gao for valuable discussions and support regarding exoplanet atmospheres and CARMA. We thank ASU faculty Hongwu Xu for help with GSAS-II analysis and Richard Hergiv for valuable discussions and providing bulk orthoenstatite. We thank Karl Weiss, Kenneth Mossman, and Manuel Roldan-Gutierrez at the John M. Cowley Center for High Resolution Electron Microscopy (CHREM) at ASU for all electron microscopy work. We thank David Wright at the Goldwater Materials Science Facility (GMSF) at ASU for help with high temperature synthesis. *This work is financially supported by NASA FINESST grant 80NSSC22K1640.*

Select References

Adams, N. 1961, The Physics and Chemistry of Surface (Oxford University Press). https://books.google.com/books/about/The_Physics_and_Chemistry_of_Surface.html?id=Q2GMAAAIAAAJ
Auer, S., Gao, P., Feller, A., & Miley, C. V. 2019, *Geochimica et Cosmochimica Acta*, 257
Bai, Z., & Berman, R. 1988, *Geochimica et Cosmochimica Acta*, 52
Bai, Z., & Berman, R. 1989, *Geochimica et Cosmochimica Acta*, 53
Bai, Z., & Berman, R. 1990, *Geochimica et Cosmochimica Acta*, 54
Bai, Z., & Berman, R. 1991, *Geochimica et Cosmochimica Acta*, 55
Bai, Z., & Berman, R. 1992, *Geochimica et Cosmochimica Acta*, 56
Bai, Z., & Berman, R. 1993, *Geochimica et Cosmochimica Acta*, 57
Bai, Z., & Berman, R. 1994, *Geochimica et Cosmochimica Acta*, 58
Bai, Z., & Berman, R. 1995, *Geochimica et Cosmochimica Acta*, 59
Bai, Z., & Berman, R. 1996, *Geochimica et Cosmochimica Acta*, 60
Bai, Z., & Berman, R. 1997, *Geochimica et Cosmochimica Acta*, 61
Bai, Z., & Berman, R. 1998, *Geochimica et Cosmochimica Acta*, 62
Bai, Z., & Berman, R. 1999, *Geochimica et Cosmochimica Acta*, 63
Bai, Z., & Berman, R. 2000, *Geochimica et Cosmochimica Acta*, 64
Bai, Z., & Berman, R. 2001, *Geochimica et Cosmochimica Acta*, 65
Bai, Z., & Berman, R. 2002, *Geochimica et Cosmochimica Acta*, 66
Bai, Z., & Berman, R. 2003, *Geochimica et Cosmochimica Acta*, 67
Bai, Z., & Berman, R. 2004, *Geochimica et Cosmochimica Acta*, 68
Bai, Z., & Berman, R. 2005, *Geochimica et Cosmochimica Acta*, 69
Bai, Z., & Berman, R. 2006, *Geochimica et Cosmochimica Acta*, 70
Bai, Z., & Berman, R. 2007, *Geochimica et Cosmochimica Acta*, 71
Bai, Z., & Berman, R. 2008, *Geochimica et Cosmochimica Acta*, 72
Bai, Z., & Berman, R. 2009, *Geochimica et Cosmochimica Acta*, 73
Bai, Z., & Berman, R. 2010, *Geochimica et Cosmochimica Acta*, 74
Bai, Z., & Berman, R. 2011, *Geochimica et Cosmochimica Acta*, 75
Bai, Z., & Berman, R. 2012, *Geochimica et Cosmochimica Acta*, 76
Bai, Z., & Berman, R. 2013, *Geochimica et Cosmochimica Acta*, 77
Bai, Z., & Berman, R. 2014, *Geochimica et Cosmochimica Acta*, 78
Bai, Z., & Berman, R. 2015, *Geochimica et Cosmochimica Acta*, 79
Bai, Z., & Berman, R. 2016, *Geochimica et Cosmochimica Acta*, 80
Bai, Z., & Berman, R. 2017, *Geochimica et Cosmochimica Acta*, 81
Bai, Z., & Berman, R. 2018, *Geochimica et Cosmochimica Acta*, 82
Bai, Z., & Berman, R. 2019, *Geochimica et Cosmochimica Acta*, 83
Bai, Z., & Berman, R. 2020, *Geochimica et Cosmochimica Acta*, 84
Bai, Z., & Berman, R. 2021, *Geochimica et Cosmochimica Acta*, 85
Bai, Z., & Berman, R. 2022, *Geochimica et Cosmochimica Acta*, 86
Bai, Z., & Berman, R. 2023, *Geochimica et Cosmochimica Acta*, 87
Bai, Z., & Berman, R. 2024, *Geochimica et Cosmochimica Acta*, 88
Bai, Z., & Berman, R. 2025, *Geochimica et Cosmochimica Acta*, 89
Bai, Z., & Berman, R. 2026, *Geochimica et Cosmochimica Acta*, 90
Bai, Z., & Berman, R. 2027, *Geochimica et Cosmochimica Acta*, 91
Bai, Z., & Berman, R. 2028, *Geochimica et Cosmochimica Acta*, 92
Bai, Z., & Berman, R. 2029, *Geochimica et Cosmochimica Acta*, 93
Bai, Z., & Berman, R. 2030, *Geochimica et Cosmochimica Acta*, 94
Bai, Z., & Berman, R. 2031, *Geochimica et Cosmochimica Acta*, 95
Bai, Z., & Berman, R. 2032, *Geochimica et Cosmochimica Acta*, 96
Bai, Z., & Berman, R. 2033, *Geochimica et Cosmochimica Acta*, 97
Bai, Z., & Berman, R. 2034, *Geochimica et Cosmochimica Acta*, 98
Bai, Z., & Berman, R. 2035, *Geochimica et Cosmochimica Acta*, 99
Bai, Z., & Berman, R. 2036, *Geochimica et Cosmochimica Acta*, 100
Bai, Z., & Berman, R. 2037, *Geochimica et Cosmochimica Acta*, 101
Bai, Z., & Berman, R. 2038, *Geochimica et Cosmochimica Acta*, 102
Bai, Z., & Berman, R. 2039, *Geochimica et Cosmochimica Acta*, 103
Bai, Z., & Berman, R. 2040, *Geochimica et Cosmochimica Acta*, 104
Bai, Z., & Berman, R. 2041, *Geochimica et Cosmochimica Acta*, 105
Bai, Z., & Berman, R. 2042, *Geochimica et Cosmochimica Acta*, 106
Bai, Z., & Berman, R. 2043, *Geochimica et Cosmochimica Acta*, 107
Bai, Z., & Berman, R. 2044, *Geochimica et Cosmochimica Acta*, 108
Bai, Z., & Berman, R. 2045, *Geochimica et Cosmochimica Acta*, 109
Bai, Z., & Berman, R. 2046, *Geochimica et Cosmochimica Acta*, 110
Bai, Z., & Berman, R. 2047, *Geochimica et Cosmochimica Acta*, 111
Bai, Z., & Berman, R. 2048, *Geochimica et Cosmochimica Acta*, 112
Bai, Z., & Berman, R. 2049, *Geochimica et Cosmochimica Acta*, 113
Bai, Z., & Berman, R. 2050, *Geochimica et Cosmochimica Acta*, 114
Bai, Z., & Berman, R. 2051, *Geochimica et Cosmochimica Acta*, 115
Bai, Z., & Berman, R. 2052, *Geochimica et Cosmochimica Acta*, 116
Bai, Z., & Berman, R. 2053, *Geochimica et Cosmochimica Acta*, 117
Bai, Z., & Berman, R. 2054, *Geochimica et Cosmochimica Acta*, 118
Bai, Z., & Berman, R. 2055, *Geochimica et Cosmochimica Acta*, 119
Bai, Z., & Berman, R. 2056, *Geochimica et Cosmochimica Acta*, 120
Bai, Z., & Berman, R. 2057, *Geochimica et Cosmochimica Acta*, 121
Bai, Z., & Berman, R. 2058, *Geochimica et Cosmochimica Acta*, 122
Bai, Z., & Berman, R. 2059, *Geochimica et Cosmochimica Acta*, 123
Bai, Z., & Berman, R. 2060, *Geochimica et Cosmochimica Acta*, 124
Bai, Z., & Berman, R. 2061, *Geochimica et Cosmochimica Acta*, 125
Bai, Z., & Berman, R. 2062, *Geochimica et Cosmochimica Acta*, 126
Bai, Z., & Berman, R. 2063, *Geochimica et Cosmochimica Acta*, 127
Bai, Z., & Berman, R. 2064, *Geochimica et Cosmochimica Acta*, 128
Bai, Z., & Berman, R. 2065, *Geochimica et Cosmochimica Acta*, 129
Bai, Z., & Berman, R. 2066, *Geochimica et Cosmochimica Acta*, 130
Bai, Z., & Berman, R. 2067, *Geochimica et Cosmochimica Acta*, 131
Bai, Z., & Berman, R. 2068, *Geochimica et Cosmochimica Acta*, 132
Bai, Z., & Berman, R. 2069, *Geochimica et Cosmochimica Acta*, 133
Bai, Z., & Berman, R. 2070, *Geochimica et Cosmochimica Acta*, 134
Bai, Z., & Berman, R. 2071, *Geochimica et Cosmochimica Acta*, 135
Bai, Z., & Berman, R. 2072, *Geochimica et Cosmochimica Acta*, 136
Bai, Z., & Berman, R. 2073, *Geochimica et Cosmochimica Acta*, 137
Bai, Z., & Berman, R. 2074, *Geochimica et Cosmochimica Acta*, 138
Bai, Z., & Berman, R. 2075, *Geochimica et Cosmochimica Acta*, 139
Bai, Z., & Berman, R. 2076, *Geochimica et Cosmochimica Acta*, 140
Bai, Z., & Berman, R. 2077, *Geochimica et Cosmochimica Acta*, 141
Bai, Z., & Berman, R. 2078, *Geochimica et Cosmochimica Acta*, 142
Bai, Z., & Berman, R. 2079, *Geochimica et Cosmochimica Acta*, 143
Bai, Z., & Berman, R. 2080, *Geochimica et Cosmochimica Acta*, 144
Bai, Z., & Berman, R. 2081, *Geochimica et Cosmochimica Acta*, 145
Bai, Z., & Berman, R. 2082, *Geochimica et Cosmochimica Acta*, 146
Bai, Z., & Berman, R. 2083, *Geochimica et Cosmochimica Acta*, 147
Bai, Z., & Berman, R. 2084, *Geochimica et Cosmochimica Acta*, 148
Bai, Z., & Berman, R. 2085, *Geochimica et Cosmochimica Acta*, 149
Bai, Z., & Berman, R. 2086, *Geochimica et Cosmochimica Acta*, 150
Bai, Z., & Berman, R. 2087, *Geochimica et Cosmochimica Acta*, 151
Bai, Z., & Berman, R. 2088, *Geochimica et Cosmochimica Acta*, 152
Bai, Z., & Berman, R. 2089, *Geochimica et Cosmochimica Acta*, 153
Bai, Z., & Berman, R. 2090, *Geochimica et Cosmochimica Acta*, 154
Bai, Z., & Berman, R. 2091, *Geochimica et Cosmochimica Acta*, 155
Bai, Z., & Berman, R. 2092, *Geochimica et Cosmochimica Acta*, 156
Bai, Z., & Berman, R. 2093, *Geochimica et Cosmochimica Acta*, 157
Bai, Z., & Berman, R. 2094, *Geochimica et Cosmochimica Acta*, 158
Bai, Z., & Berman, R. 2095, *Geochimica et Cosmochimica Acta*, 159
Bai, Z., & Berman, R. 2096, *Geochimica et Cosmochimica Acta*, 160
Bai, Z., & Berman, R. 2097, *Geochimica et Cosmochimica Acta*, 161
Bai, Z., & Berman, R. 2098, *Geochimica et Cosmochimica Acta*, 162
Bai, Z., & Berman, R. 2099, *Geochimica et Cosmochimica Acta*, 163
Bai, Z., & Berman, R. 2100, *Geochimica et Cosmochimica Acta*, 164
Bai, Z., & Berman, R. 2101, *Geochimica et Cosmochimica Acta*, 165
Bai, Z., & Berman, R. 2102, *Geochimica et Cosmochimica Acta*, 166
Bai, Z., & Berman, R. 2103, *Geochimica et Cosmochimica Acta*, 167
Bai, Z., & Berman, R. 2104, *Geochimica et Cosmochimica Acta*, 168
Bai, Z., & Berman, R. 2105, *Geochimica et Cosmochimica Acta*, 169
Bai, Z., & Berman, R. 2106, *Geochimica et Cosmochimica Acta*, 170
Bai, Z., & Berman, R. 2107, *Geochimica et Cosmochimica Acta*, 171
Bai, Z., & Berman, R. 2108, *Geochimica et Cosmochimica Acta*, 172
Bai, Z., & Berman, R. 2109, *Geochimica et Cosmochimica Acta*, 173
Bai, Z., & Berman, R. 2110, *Geochimica et Cosmochimica Acta*, 174
Bai, Z., & Berman, R. 2111, *Geochimica et Cosmochimica Acta*, 175
Bai, Z., & Berman, R. 2112, *Geochimica et Cosmochimica Acta*, 176
Bai, Z., & Berman, R. 2113, *Geochimica et Cosmochimica Acta*, 177
Bai, Z., & Berman, R. 2114, *Geochimica et Cosmochimica Acta*, 178
Bai, Z., & Berman, R. 2115, *Geochimica et Cosmochimica Acta*, 179
Bai, Z., & Berman, R. 2116, *Geochimica et Cosmochimica Acta*, 180
Bai, Z., & Berman, R. 2117, *Geochimica et Cosmochimica Acta*, 181
Bai, Z., & Berman, R. 2118, *Geochimica et Cosmochimica Acta*, 182
Bai, Z., & Berman, R. 2119, *Geochimica et Cosmochimica Acta*, 183
Bai, Z., & Berman, R. 2120, *Geochimica et Cosmochimica Acta*, 184
Bai, Z., & Berman, R. 2121, *Geochimica et Cosmochimica Acta*, 185
Bai, Z., & Berman, R. 2122, *Geochimica et Cosmochimica Acta*, 186
Bai, Z., & Berman, R. 2123, *Geochimica et Cosmochimica Acta*, 187
Bai, Z., & Berman, R. 2124, *Geochimica et Cosmochimica Acta*, 188
Bai, Z., & Berman, R. 2125, *Geochimica et Cosmochimica Acta*, 189
Bai, Z., & Berman, R. 2126, *Geochimica et Cosmochimica Acta*, 190
Bai, Z., & Berman, R. 2127, *Geochimica et Cosmochimica Acta*, 191
Bai, Z., & Berman, R. 2128, *Geochimica et Cosmochimica Acta*, 192
Bai, Z., & Berman, R. 2129, *Geochimica et Cosmochimica Acta*, 193
Bai, Z., & Berman, R. 2130, *Geochimica et Cosmochimica Acta*, 194
Bai, Z., & Berman, R. 2131, *Geochimica et Cosmochimica Acta*, 195
Bai, Z., & Berman, R. 2132, *Geochimica et Cosmochimica Acta*, 196
Bai, Z., & Berman, R. 2133, *Geochimica et Cosmochimica Acta*, 197
Bai, Z., & Berman, R. 2134, *Geochimica et Cosmochimica Acta*, 198
Bai, Z., & Berman, R. 2135, *Geochimica et Cosmochimica Acta*, 199
Bai, Z., & Berman, R. 2136, *Geochimica et Cosmochimica Acta*, 200
Bai, Z., & Berman, R. 2137, *Geochimica et Cosmochimica Acta*, 201
Bai, Z., & Berman, R. 2138, *Geochimica et Cosmochimica Acta*, 202
Bai, Z., & Berman, R. 2139, *Geochimica et Cosmochimica Acta*, 203
Bai, Z., & Berman, R. 2140, *Geochimica et Cosmochimica Acta*, 204
Bai, Z., & Berman, R. 2141, *Geochimica et Cosmochimica Acta*, 205
Bai, Z., & Berman, R. 2142, *Geochimica et Cosmochimica Acta*, 206
Bai, Z., & Berman, R. 2143, *Geochimica et Cosmochimica Acta*, 207
Bai, Z., & Berman, R. 2144, *Geochimica et Cosmochimica Acta*, 208
Bai, Z., & Berman, R. 2145, *Geochimica et Cosmochimica Acta*, 209
Bai, Z., & Berman, R. 2146, *Geochimica et Cosmochimica Acta*, 210
Bai, Z., & Berman, R. 2147, *Geochimica et Cosmochimica Acta*, 211