Program: Techniques and Technologies for Investigating the Interior Structure of Venus

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JPL PI: James A. Cutts

Co-Investigators:
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David L. Mimoun, Raphael Garcia (ISAE)
Philippe Lognonné (IPGP)
Gerald Schubert (UCLA)
Sebastien Lebonnois (LMD)

Brief summary of progress to date

Venus mineralogy and geophysical properties (Leads: Jackson, Zhan)

Postdoctoral scholars Gregory Finkelstein (Mineral Physics) and Justin Ko (Seismology) with graduate student Natalia Solomatova (Mineral Physics) and undergraduate Tyler Perez (3rd year in Planetary Science, Caltech) have progressed very well with experimental work establishing constraints on phase transformations and magnetic properties of candidate Venus crustal materials (hydrous and anhydrous) under relevant Venus crustal conditions. Specifically, these properties are: (1) volumetric collapse that could trigger phase transformational faulting, thus triggering a Venusian quake, (2) oxidation and magnetic state changes in iron that may help understand volatile cycling in the' crust and interior (Figures 1-3). We have observed transitions in a hydrated iron sulfate composition at elevated pressures and silicate glasses. With KISS postdoctoral scholar Justin Ko, we are incorporate our results into earthquake modeling and propagation through Venus' dense atmosphere.

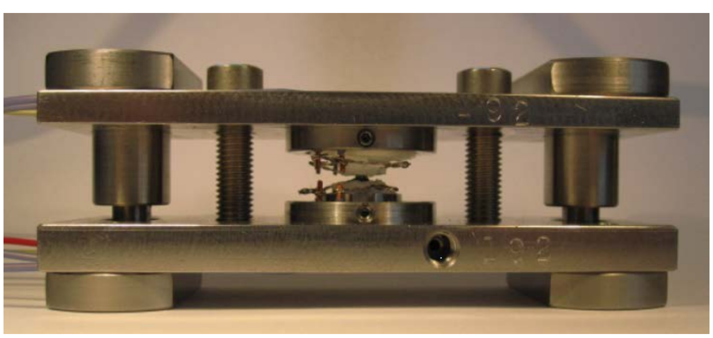


***Figure 1.** The hydrothermal diamond anvil cell is used for recreating deep crustal conditions on Venus.*

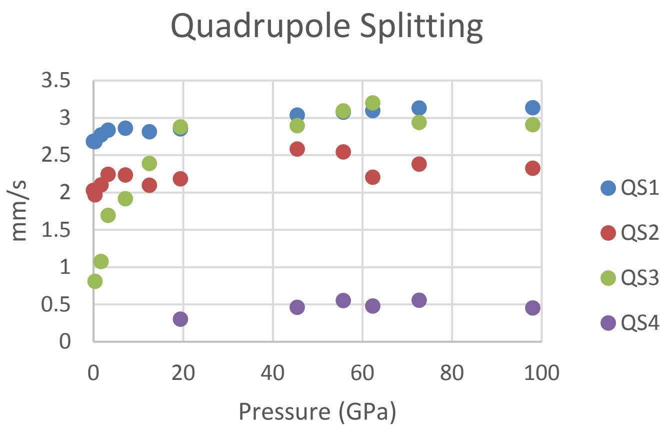


Figure 2. *Preliminary analysis of the hyperfine fields (quadrupole splitting) of four distinct iron sites in szomolnokite, a hydrated iron sulfate mineral, up to pressures of the Venusian lower mantle (Perez et al. 2017, in preparation). Note that a transition is occurring at relatively low pressure (crustal conditions).*

Figure 3. *Conventional Mössbauer spectra for (a) rhyolitic glass and (b) basaltic glass at room pressure and temperature, and the corresponding best fits using CONUSS. Blue and red lines correspond to site 1 and site 2, respectively. Insets show modeled time-domain spectra. Reduced silicate glasses used in this study were synthesized at the iron-wüstite buffer by M. Roskosz, Institut de Minéralogie, Physique des Materiaux et Cosmochimie, Muséum National d'Histoire Naturelle. More detailed spectral analysis of these data and those from high pressure data collected in time-domain are presented in Solomatova et al. (2017, in preparation).*

Theoretical investigation of the role of the Venus atmosphere and atmosphere- surface interaction on seismic studies of the interior of Venus (Leads: Schubert, Lebonnois, Garcia)

A major accomplishment of the KISS study was the recognition that Venus quakes will produce strong infrasonic signals that can be detected as pressure waves at altitudes in the Venus atmosphere where long duration observations are possible with existing technology. Progress towards this end includes the numerical modeling (finite difference simulations) of atmospheric acoustic and gravity waves created by seismic surface waves propagating in Venus interior is performed in a windy and attenuating atmosphere model provided by latest GCM simulations of S. Lebonnois. The atmosphere is forced from below by the Venus surface with dispersive surface waves propagating at 4 km/s. Our study focuses on the effects of the strong winds present in Venus atmosphere on the acoustic wavefront.

Recent finite differences simulations computed air density and temperatures variations in order to prepare computations of variations of C02 Non-LTE (4.3 µm) emissions by Miguel Lopez Valverde at IAA (Spain) (Fig. 4).

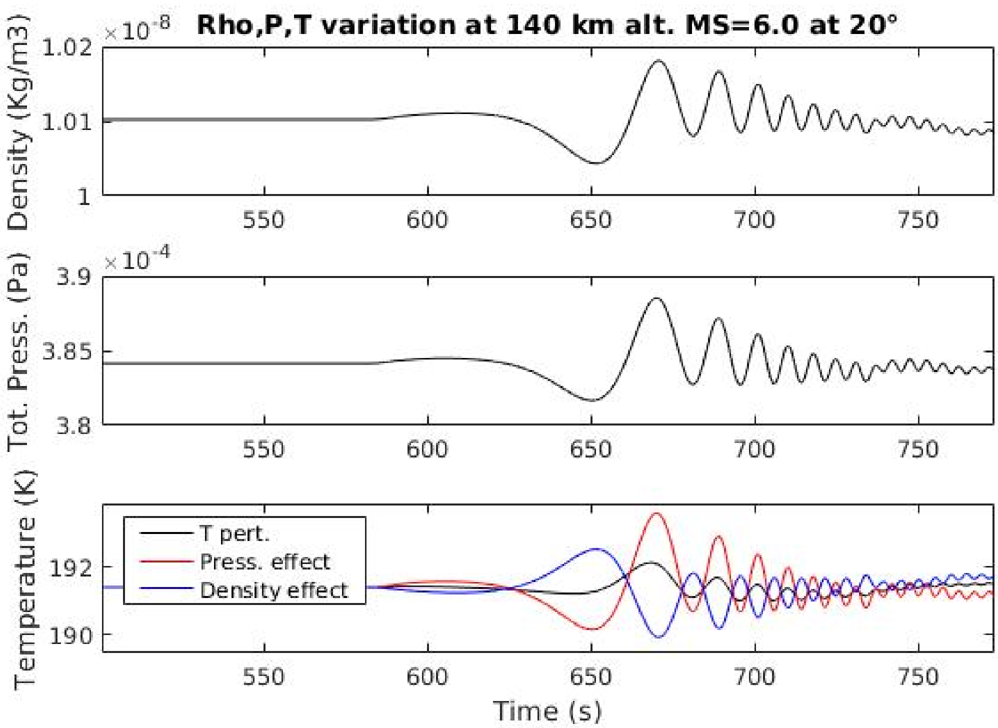


Figure 4. From top to bottom, air density, pressure and temperature variations at midday local time and 140 km altitude in Venus atmosphere from a simulated infrasonic wave front generated by seismic rayleigh waves. Bottom panel explicit pressure and density effects on temperature variations.

In addition, we investigate the conditions present in the deep atmosphere of Venus, as they may affect the simulations for the propagation of waves. The temperature profile measured by the VeGa-2 probe in 1985 leads us to the possibility of a vertical gradient in the N_2 mixing ratio in a layer 7-km thick above the surface. We are investigating this hypothesis, and consequences for the waves will be studied in the next step (Lebonnois & Schubert 2107, under review).

Balloon-borne infrasonic measurements (Leads: Cutts, Pauken, Mimoun)

Another major accomplishment of the KISS study was the recognition that Venus quakes will produce strong infrasonic signals that can be detected as pressure waves at altitudes in the Venus atmosphere where long duration observations are possible with existing technology. We are examining the feasibility of sending Cubesats or Smallsats to Venus to perform such scientific missions (Fig. 5). Activities include: modeling the wave propagation (1 PhD student, 2 undergraduate students), understanding the background noise (2 undergraduate students), and preliminary terrestrial balloon experiment instrument design (1 engineer, 2 undergraduate students). Microbarometers have been secured and are undergoing acceptance tests. Venus atmospheric models are provided by S. Lebonnois' work (see above section).

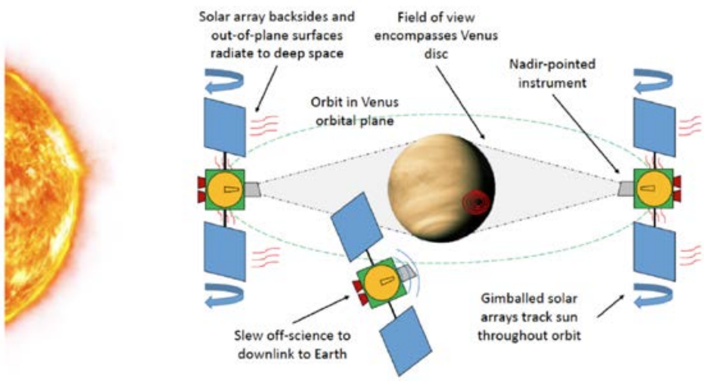
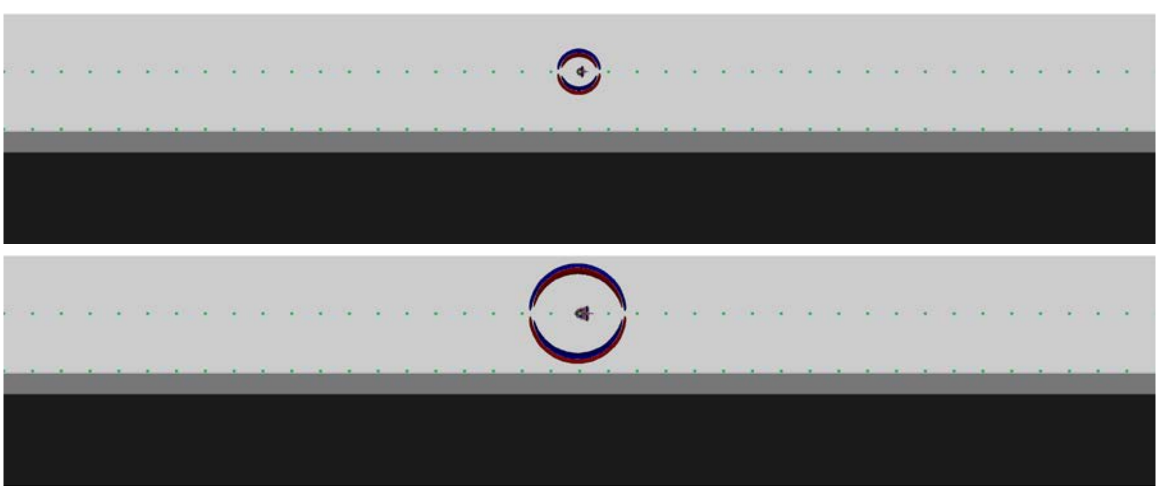


Figure 5. Infrared monitoring of Venus with Smallsat. Study of Venus Airglow Measurement Orbiter for Seismicity (VAMOS). concept was funded by JPL internal funds. Led to proposal for Planetary Science Deep Space SmallSat Studies.

A new code fully coupling SPECFEM seismological tool with a realistic atmosphere is now available (Brissaud et al. 2017, in press). This tool has been adapted to the specific attenuation of CO_2 atmospheres. Figure below present some tests for an atmospheric explosion in Mars atmosphere. The seismic waves generated by the acoustic wavefront of the explosion propagate in a solid medium with sand layers (S waves velocities as low as 270 m/s, thickness of layers as low as 50 m). This test case demonstrate the stability of the code at high frequencies and for low material rigidity. The application of the code to the balloon experiment in such a desert like medium is now straight forward in terms of propagation simulation. Q. Brissaud and R.F. Garcia will supervise a master student to insert the seismic hammer source and run the simulations.



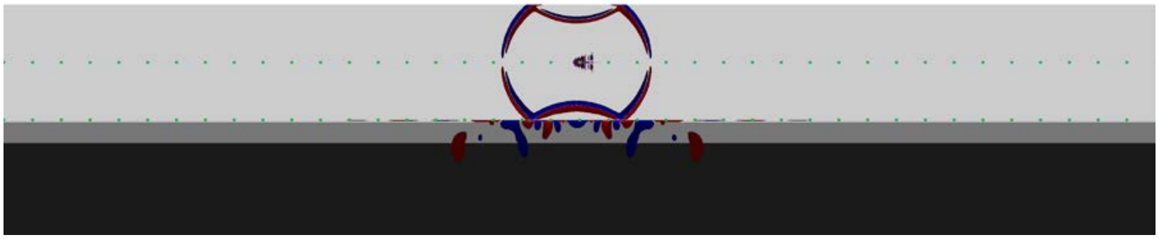


Figure 6. Simulation of an explosion in Mars atmosphere and ground (snapshots at 5, 10 and 15 s after explosion of vertical velocity perturbation). Size of the domain is 10x50 km. Wind and attenuation are presents. The contact between the acoustic wave and the ground generate seismic waves in the lower part of the domain.

We are assessing the feasibility of a balloon acoustic monitoring system by conducting a flight experiment on Earth. This flight experiments will focus on using barometer instruments on a tethered helium-filled balloon in the vicinity of a known seismic source generated by a seismic hammer. We will assess conducting such measurements on Venus, including seismic and aseismic energy sources and propagation through its atmosphere.

In addition to collaborating within the KISS team, JPL has developed a no exchange of funds collaboration with the Sandia Laboratories to carry out a series of tests with high explosive infrasound sources with tests planned for May 2017 and November 2017. The results will be shared with the team.

Status of Collaborations and Team Meetings (Campus/JPL/External)

We are progressing well with our Technical Development project goals with lines of communication amongst all involved. Our team of scientists and technologists from Caltech, JPL, UCLA and three French research institutions are undertaking the critical experiments and modeling needed to propose future space flight experiments and ultimately a dedicated mission. We hold bi-monthly meetings with all team members, and more regular meetings within the teams. We hold informative lunch gatherings at the AGU Meetings, where more than a dozen members, students, and postdocs attended (2015 & 2016).

We sponsored a pizza lunch at KISS on March 15, 2017. The lunch followed a Noon seminar given by Giovanni Occhipinti (IPGP, France), “The recent history of Ionospheric Seismology from Sumatra 2004 to Chile 2015 through the revolutionary observations of Tohoku-Oki 2011”. The seminar took place in the Benioff Room in South Mudd (Caltech) and was of interest to our KISS-Venus team. The discussions continued during lunch and lasted until about 5pm in the Black Hole Conference Room at KISS. We include some pictures at the end of this report.

Papers / Technical Reports to date (Alphabetical)

Brissaud, Q., R. Martin, R.F. Garcia, D. Komatitsch (2017): ***Hybrid Galerkin numerical modeling of elastodynamics and compressible Navier-Stokes couplings: applications to seismo-gravito acoustic waves***, Geophys. J. Int., in press.

Brissaud Q., R. Martin, R.F. Garcia, D. Komatitsch (2016): ***Finite-difference numerical modelling of gravito-acoustic wave propagation in a windy and attenuating atmosphere***, Geophys. J. Int., doi: 10.1093/gji/ggw121.

Finkelstein, G.J., J. M. Jackson, W. Sturhahn, D. Zhang, E. E. Alp, and T. S. Toellner (2017): ***Single-crystal equations of state of magnesiowüstite at high pressures***, American Mineralogist, under review.

Garcia, R.F., Q. Brissaud, L. Rolland, R.Martin, D. Komatitsch, A. Spiga, P. Lognonné, B. Banerdt (2016): ***Finite-Difference Modeling of Acoustic and Gravity Wave Propagation in Mars Atmosphere: Application to Infrasounds Emitted by Meteor Impacts***, Space Science Reviews, doi:10.1007/s11214-016-0324-6.

Lebonnois S. and G. Schubert (2017): **Possible density-driven separation of CO_2 and N_2 in the deep atmosphere of Venus**. Nature Geoscience, under review.

Presentations / Conferences to date (Chronological order)

2017

Kenda, B., P. Lognonné, A. Komjathy, B. Banerdt, J. Cutts, L. Soret, and J. Jackson (2017): ***Investigating the Concept of Using Airglow Measurements to Detect Seismicity on Venus***. Session SM5.5/PS1.5 Extraterrestrial seismology – Advances in instrumentation and methodology, European Geosciences Union, Vienna, Austria.

Mimoun, D., R. Garcia, A. Cadu, J. Cutts, A. Komjathy, M. Pauken, S. Kedar, J. Jackson, and D. Stevenson (2017): ***Exploring Venus interior structure with infrasonic techniques***. Session SM5.5/PS1.5 Extraterrestrial seismology – Advances in instrumentation and methodology, European Geosciences Union, Vienna, Austria.

Kenda, B. P. Lognonné, A. Komjathy, B. Banerdt, J. Cutts, L. Soret, J. Jackson, (2017): ***Exploring the Use of Airglow Measurements for Detecting Seismicity on Venus***, Session S.20 Earth and planetary space and remote sensing seismology, i.e. seismology without seismometer, Joint Scientific Assembly of the International Association of Geodesy and the International Association of Seismology and Physics of Earth's Interior, Kobe, Japan.

2016

Finkelstein, G.J., J. M. Jackson, W. Sturhahn, D. Zhang, E. E. Alp, and T. S. Toellner (2016): ***Defect structures of Magnesiowüstite and Wüstite from Hybrid-Mode Synchrotron Mössbauer Spectroscopy***. Fall AGU Meeting in San Francisco, California.

Jackson, J.M., James A. Cutts, Michael Pauken, Attila Komjathy, Suzanne Smrekar, Sharon Kedar, David Mimoun, Raphael Garcia, Gerald Schubert, S.ebastien Lebonnois, David J. Stevenson, Philippe Lognonné , Zhonwen Zhan, Justin Ko, and Victor Tsai (2016): ***Exploring the interior of Venus with seismic and***

infrasonic techniques. Ionospheric and Atmospheric Monitoring of Natural Hazards: Existing Terrestrial and Potential Planetary Applications II, Fall AGU Meeting in San Francisco, California (NH53D-06: 122988). *Invited.*

Ko, Y.-T. (Justin) and Z. Zhan (2016): ***A two-step full waveform inversion technique based on the WKM method***, Fall AGU Meeting in San Francisco, California (DI23A-2601), San Francisco, CA

Solomatova, N.V. J. M. Jackson, W. Sturhahn, and M. Roskosz (2016): ***The electronic structure of iron in rhyolitic glass at high pressure***. Fall AGU Meeting in San Francisco, California (DI52A-08). Oral presentation.

Komjathy, A., J. Cutts, M. Pauken, S. Kedar, S. Smrekar, J. Hall, A Didion, B. Kenda, J. Jackson, D. Mimoun, R. Garcia and P. Lognonné (2016): ***Infrasound as a Geophysical Probe Using Earth as a Venus Analog***, Presented at the 2016 AGU Meeting, San Francisco, CA, Dec 12-16.

Cutts, J., A. Didion, A. Komjathy, C. Sotin and M. Wallace (2016): ***Venus Smallsat and Cuvesat Mission***, Presented at the 14^{th} VEXAG Meeting, Nov 29 to Dec 1.

Komjathy, A., Cutts, J., M. Pauken, S. Kedar, J. Jackson J, S. Smrekar, D. Mimoun and R. Garcia (2016): ***Infrasound as a Geophysical Probe Using Earth as a Venus Analog***, Presented at the DPS 48/ EPSC 11 Meeting of the American Astronomical Society, Pasadena, CA, Oct 16-21.

Lebonnois S. and G. Schubert (2016): **A density-driven separation of CO_2 and N_2 in the deep atmosphere of Venus**. Presented at the DPS 48/EPSC 11 Meeting of the American Astronomical Society, Pasadena, CA, Oct 16-21.

Cutts, J., M. Pauken, J. Jackson, D, Mimoun, R. Garcia, D. Bowman, A. Komjathy, S. Kedar and members of the KISS Venus Interior Study Team (2016): ***Venus Exploration with Infrasound Techniques***, Presented at the 13th International Planetary Probe Workshop, Presented at JHUAPL, June 13-17.

Garcia, R.F., D. Mimoun, S. Lebonnois, Q. Brissaud, G. Poler (2016): ***Infrasounds from Venus quakes: Numerical modeling and balloon observation project.*** Presented at *International Venus Conference 2016* at Oxford, April 4-8.

Cutts, J.A., M. Pauken, J. M. Jackson, D. Mimoun, and Members of the Keck Institute for Space Studies Study and Development Teams (2016): ***Venus: Exploring its interior with seismic and infrasonic techniques***. Presented at *International Venus Conference 2016* at Oxford, April 4-8.

Undergraduate students, graduate students and postdocs who have worked on the project

- Graduate Students: Quentin Brissaud (ISAE-SUPAERO, France), Tibor Durgonics (Danish Technical University, Denmark, JPL), Balthasar Kenda (IPGP, France, JPL), Itaru Ohira (Tohoku University, Japan, Caltech), Giorgio Savastano (University of Rome “La Sapienza”, Italy, JPL), Natalia Solomatova (Caltech)
- Postdoctoral Scholars: Dr. Gregory Finkelstein (Caltech), Dr. Justin Ko (Caltech)
- Undergraduate Student: Tyler Perez (Caltech)

Pictures

KISS-Venus Team Meeting: March 15, 2017. Black Hole Conference Room, Keck Institute for Space Studies. From Left to Right: Jim Cutts, Georgio Sevastano, Panagiotis Vergados, Balthasar Kenda, Jennifer Jackson, Giovanni (aka “Ninto”) Occhipinti, Attila Komjathy, and Tibor Durgonics.

KISS-Venus Team Meeting: March 15, 2017 Black Hole Conference Room, Keck Institute for Space Studies.

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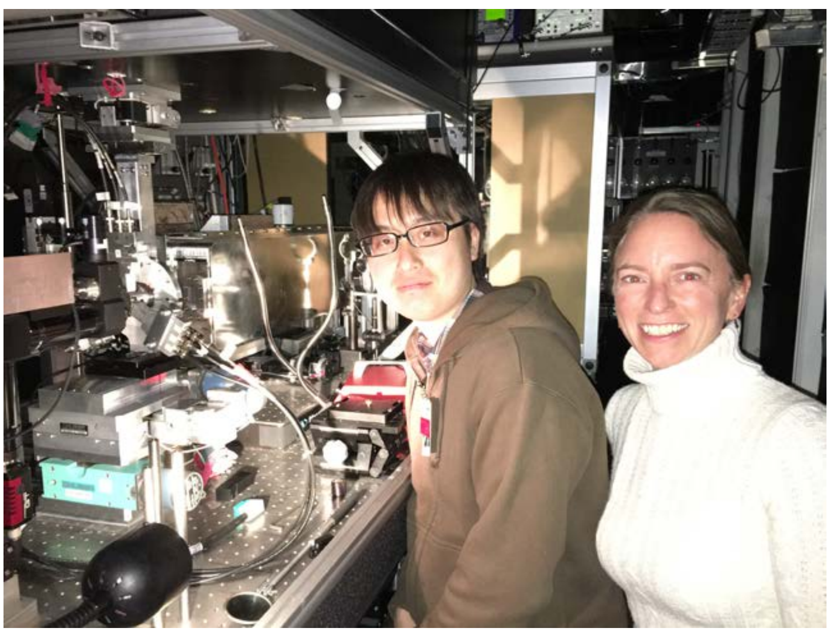
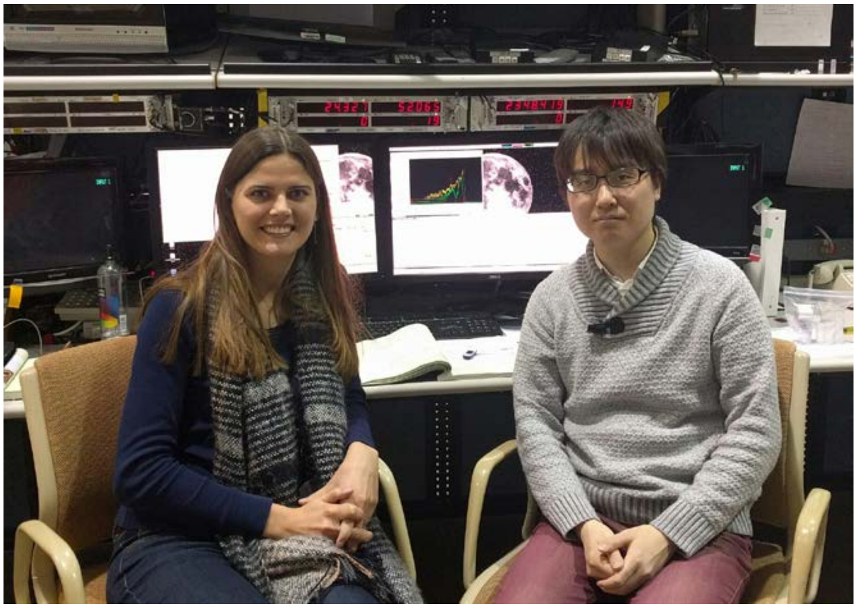


KISS-Venus student (Itaru Ohira, visiting student from Tohoku University, Japan) and Jennifer Jackson inside the experimental hutch, preparing nuclear resonant scattering experiments at Sector 3 of the Advanced Photon Source, Chicago area, IL.


KISS-Venus graduate students (Natalia Solmatova, Caltech) and Itaru Ohira ((Itaru Ohira, visiting student from Tohoku Universtiy, Japan) conducting nuclear resonant scattering experiments at Sector 3 of the Advanced Photon Source, Chicago area, IL.