Russel Hemley and Ho-kwang Mao

2005 Balzan Prize for Mineral Physics
For the impressive impact of their joint work leading to fundamental breakthroughs, theoretical and experimental, in the field of minerals submitted to extreme physical conditions. They have operated as a highly effective team, characterized by twenty years of research contributions at the highest level. They have developed techniques which allow them to study the behaviour of a wide range of materials, such as hydrogen, the most abundant "mineral" in the universe. Their results have deep implications for our understanding of nature.

New Directions in Mineral Physics: Multidisciplinary High Pressure Science

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With the second half of their Balzan Prize, Russell Hemley and Ho-kwang Mao are implementing a project focused on bringing bright young people from diverse backgrounds into the multidisciplinary field of High Pressure Science. Recent advances in mineral physics are unleashing the power of high pressure research to tackle a broad range of great challenges that span numerous scientific disciplines. Breakthroughs are expected in applications of high pressure research to mineralogy, geophysics, geochemistry and bioscience, as well as specific areas such as hydrogen storage, superhard materials and superconductivity. We are thus coming close to solving mysteries like the Earth's inner core and the roots of plate tectonics. The project is focused on training and its goal is the exploration of the new high-pressure dimension in multidisciplinary physical sciences. The fellowships encourage the development, design, and fabrication of new instrumentation that exploit the CVD diamond technology developed by Hemley and Mao. Publications and dissemination of results are also being financed.
- Dr. Pierre Beck is a Balzan Award supported post-doctoral associate who was trained in high-pressure meteorite impact phenomena at the Ecole Normale Superieure in Lyon, France. Prior to joining Hemley and Mao, he published a series of papers on meteorite studies including an important article in "Nature" in 2005. As part of his Balzan-supported project, he is developing time-resolved (i.e., dynamic) high pressure-temperature phenomena with diamond anvil cells. His work has led to the first high pressure-temperature Raman studies of olivine and to a

novel method for measuring the thermal conductivity of materials at high pressures and temperatures, with two papers and a series of abstracts in press. This is part of Hemley and Mao's Balzan-supported project to develop combined static and dynamic (i.e., shock-wave) compression science.

- Dr. Lin Wang is a Balzan Award supported post-doctoral associate who has received his Ph.D. degree from Jilin University, China. He developed a new method for the synthesis of controlled shape C60 fullerene nanorods. Further high-pressure/temperature treatments lead to polymerization and transitions to tetragonal, orthorhombic, or rhombohedral phases. These nanorods exhibit very rich nano effects in their optical, structural, phase transition, and compressional properties but lack an in situ probe to characterize the structure directly. Dr. Wang is developing a new technique to integrate the high-pressure diamond anvil cell with the high-brilliance x-ray beam focused down to 50-200 nm size at the Advanced Photon Source. This will open a new field of single-crystal x-ray nanocrystallography that will explore the correlation between crystal structure, dimensionality, and size of nanomaterials under high pressures. With Balzan Award support, Dr. Lin Wang has been working at the High Pressure Synergetic Consortium (HPSynC) at the Advanced Photon Source (APS), Argonne National Laboratory (ANL) in 2008. He is pioneering the x-ray nanocrystallographic studies that explore the correlation between crystal structure, dimensionality, and size of nanomaterials under high pressures.

- Mr. Charles Qiaoshi Zeng received Balzan Award support from September 1 to December 31, 2008. Mr. Zeng is a pre-doctoral fellow from Zhejiang University, China who had done a superb job both at Geophysical Laboratory and APS. Mr. Zeng has conducted numerous x-ray diffraction experiments at APS synchrotron facility. Most recently, he has discovered a new type of alloy and a new phenomenon in metallic glass that have far-reaching impact in fundamental physics as well as materials applications. This discovery, published in PNAS as "Novel Substitutional Alloy of Ce and Al" was selected "In This Issue" section highlights particularly interesting articles published in the February 24, 2009 print issue of PNAS.

Several high school students who also received Balzan Award support are Andrew Kung, Daniel Cohen, Alexander Levedahl, Claire Barkett, Maura James, Manchali Madurri, and Jaqueline Rivera.

- Mr. Andrew Kung is a high school student who received Balzan Award support to develop a high-pressure project studying the pressure, temperature, and temporal effects on a newly discovered O_2-H_2 alloy. This alloy was synthesized by compressing water into high-pressure phase ice VII and irradiated by x-rays, splitting the

H_2O molecules into O_2 and H_2. At ordinary pressure, O_2 reacts explosively with H_2 to form H_2O, but they coexist stably at high pressures. Mr. Kung used Raman spectroscopy as an in situ diagnostic probe to find the amounts of O_2 and H_2 in the alloy and their changes with pressure, temperature, and time. The study provides important information about this novel material and its possible energy and environmental applications.

- Mr. Daniel Cohen is a high school student who received Balzan Award support to study novel electronic phenomena in diamond. Hemley and Mao have extended their previous methods for growing large single crystal diamond by chemical vapor deposition (CVD) to include very high levels of doping with nitrogen. The goal of Mr. Cohen's project is to produce a new material with metallic electrical conductivity, and possibly superconductivity. The project involves careful measurement of electrical resistivity as a function of temperature from 4–500 K of well characterized nitrogen-doped CVD diamond that Hemley and Mao produce in their laboratory.

- Mr. Alexander Levedahl is a high school student who received Balzan Award support to investigate the high pressure-temperature behavior of hydrogen-containing ice materials known as hydrogen clathrates. These newly discovered materials are important for a broad range of problems, including understanding planetary evolution and climate change, as well as the development of new hydrogen storage materials. The experiments use laser spectroscopy techniques to determine the melting curve and new possible high pressure-temperature solid phases containing H_2 and H_2O.

- Ms. Claire Barkett is a high school student at Good Counsel High School in Olney, MD and was at Carnegie during the 2008-2009 school year. Ms. Barkett received Balzan Award support as she followed up on the earlier work of Jaqueline Rivera by synthesizing several solid solutions in the Fe_2O_3-Al_2O_3 system very close to the 1:1 $FeAlO_3$ composition. Because $FeAlO_3$ has a completely different structure than the rest of the Fe_2O_3-Al_2O_3 join, which have the rhombohedral corrundum structure isostructural with the end members, it is of interest to know the precise range of compositions where the $FeAlO_3$ structure is stable. The careful chemical synthesis methods developed and carried out in this work are therefore crucial. Diffraction measurements on these materials will allow a refinement of work carried out in the 1950s, and aid in understanding the role of magnetic interactions between ferric ions in stabilizing the $FeAlO_3$ structure.

- Ms. Maura James received Balzan Award support in the summer of 2008. Ms. James is a high school student from the Convent of the Sacred Heart in Greenwich,

CT. She investigated high pressure clathrate formation in the H_2O-NH_2- H_2 ternary system with Stephen Gramsch and Maddury Somayazulu. This was an exploratory project in which Ms. James worked out special techniques for sample loading and mapping the composition of the mixture inside the diamond anvil cell. Using Raman spectroscopy, she found that with increasing pressure, the ammonium hydroxide-H_2 mixture separates into two phases, a water-rich phase and an ammonia-rich phase that appears be composed of a clathrate containing the hydrogen molecules.
- Ms. Manchali Madurri is a high school student at Thomas Jefferson High School in Alexandria, VA. Ms. Madduri received Balzan Prize support in the summer of 2008 for her study of H_2-crown ether complexes at high pressure. Using Raman spectroscopy to track the vibrational properties of both the crown ether host and the complexed hydrogen molecules, she found that crown ether-hydrogen complexation is promoted by applied pressure, and that the optimal crown ether ring size for effective complexation of hydrogen is approximately 1.7-2.2 Å. This complexation appears to be enhanced upon decompression from pressures of approximately 5 GPa, a result that has important implications for the use of such materials in hydrogen storage applications. As a result of her work, Ms. Madduri was named a semi-finalist in both the Intel and Seimens national science fair competitions.
- Ms. Jaqueline Rivera was a high school student from the Cesar Chavez High School in Washington, DC and received Balzan Award support during the summer of 2008. Ms. Rivera developed new room-temperature, solution-based synthesis methods for solid solutions in the Fe_2O_3-Al_2O_3 solid solution system. These methods ensure that the resulting material is as homogeneous as possible, but allow precise control of composition. This particular series of compounds can serve as a model system for understanding the effect of alluminum on the concentration of ferric iron, ferrous iron and oxygen vacancies in deep mantle minerals, particularly silicate perovskite and post-perovskite. The concentration and role of ferric iron in the deep mantle has important consequences for many high-pressure mineral properties. Ms. Rivera is now studying biochemistry at the Catholic University of America.

Publications (in chronological order):

- Beck, P., A. F. Goncharov, and R. J. Hemley, *High-pressure high temperature Raman spectroscopy of San Carlos olivine*, Eos Trans. AGU Fall Meet., Suppl., 87, 2006.
- Banighan, E. J., R. Caracas, P. Beck, and R. J. Hemley, *Theoretical and experimental Raman study of spinel*, Eos Trans. AGU Fall Meet., Suppl., 87, 2006.

- Beck, P., A. F. Goncharov, V. V. Struzhkin, B. Militzer and R. J. Hemley, *Measurements of thermal diffusivity under planetary interior P-T conditions*, 37th Annual Lunar Planetary Science Conference (League City, TX, March 12-16, 2007, 2007).
- Beck, P., A. F. Goncharov, V. Struzhkin, B. Militzer and R. J. Hemley, *Measurements of thermal diffusivites under planetary interiors pressure temperature conditions*, 2007 Stewardship Science Academic Alliances Program Symposium (Washington, DC, February 5-7, 2007).
- Somayazulu, M., A. Levedahl, A. Goncharov, H. K. Mao and R. J. Hemley, *High pressure-temperature Raman spectroscopy of* H^2- H^2*O clathrate*, Bull. Am. Phys. Soc. (APS March Meeting) (Denver, CO, March 5-9, 2007).
- Beck, P., A. F. Goncharov, V. V. Struzhkin, B. Militzer, H. K. Mao, and R. J. Hemley, *Measurement of thermal diffusivity at high pressure using a transient heating technique*, Appl. Phys. Lett., 91, 181914, 2007.
- Meng, Y. F., C. S. Yan, J. Lai, S. Krasnicki, H. Shu, Q. Liang, H. K. Mao, and R. J. Hemley, *Enhanced optical properties of chemical vapor deposited single crystal diamond by low-pressure/high-temperature annealing*, Proc. Nat. Acad. Sci., 105, 17620-17625, 2008.
- Goncharov, A. F., B. Haugen, V. V. Struzhkin, P. Beck, and S. D. Jacobsen, *Radiative conductivity and oxidation state of iron in the Earth's lower mantle*, Nature, 456, 231-234, 2008.
- Liang, Q., C. S. Yan, Y. Meng, J. Lai, S. Krasnicki, T. Yu, H. Shu, H. K. Mao, and R. J. Hemley, *Ultratough single crystal diamonds by MPCVD*, Intertech 2008 (Orlando, FL, May 5-7, 2008).
- Liang, Q., C. S. Yan, Y. F. Meng, J. Lai, S. Krasnicki, T. Yu, H. Shu, H. K. Mao, and R. J. Hemley, *Recent progress in fabrication of high quality single crystal diamond at high growth rates*, Lithosphere petrology and origin of diamond International Symposium (Novosibirsk, Russia, June 5-7, 2008).
- Liu, H., L. Wang, X. Xiao, F. De Carlo, J. Feng, H. K. Mao, and R. J. Hemley, *Anomalous pressure-induced behavior of amorphous selenium from synchrotron x-ray diffraction and microtomography*, Proc. Nat. Acad. Sci., 105, 13229-13234, 2008.
- Meng, Y. F., C. S. Yan, J. Lai, S. Krasnicki, H. Shu, Q. Liang, H. K. Mao, and R. J. Hemley, *Enhanced optical properties of chemical vapor deposited single crystal diamond by low-pressure/high-temperature annealing*, Proc. Nat. Acad. Sci., 105, 17620-17625, 2008.
- Meng, Y. F., C. S. Yan, J. Lai, S. Krasnicki, H. Y. Shu, T. Yu, Q. Liang, H. K. Mao,

and R. J. Hemley, *High-temperature/low-pressure annealing of SC-CVD diamond*, 2nd International Conference on New Diamond and Nano Carbons (NDNC2008) (Taiwan, May 26-29, 2008).
- Goncharov, A. F., P. Beck, V. V. Struzhkin, R. J. Hemley, and J. C. Crowhurst, *Laser heating diamond anvil cell studies of simple molecular systems at high pressures and temperatures*, J. Phys. Chem. Solids, 69, 2217-2222, 2008.
- Goncharov, A. F., B. Haugen, V. V. Struzhkin, P. Beck, and S. D. Jacobsen, *Radiative conductivity and oxidation state of iron in the Earth's lower mantle*, Nature, 456, 231-234, 2008.
- Goncharov, A. F., S. D. Jacobsen, V. V. Struzhkin, and P. Beck, *Optical properties of minerals in the deep-earth*, in *McGraw Hill 2008 Yearbook of Science & Technology* 242-245 (McGraw Hill, New York, 2008).
- Jia, L., J. R. Sun, F. W. Wang, T. Y. Zhao, H. W. Zhang, B. G. Shen, D. X. Li, S. Nimori, Y. Ren, and Q. S. Zeng, *Volume dependence of the magnetic coupling in LaFe13−xSix based compounds*, Appl. Phys. Lett., 92, 101904, 2008.
- Zeng, Q., Z. He, X. San, Y. Ma, F. Tian, T. Cui, B. Liu, G. Zou, and H. K. Mao, *A new phase of solid iodine with different molecular covalent bonds*, Proc. Nat. Acad. Sci., 105, 4999-5001, 2008.
- Goncharov, A. F., P. Beck, V. V. Struzhkin, B. D. Haugen, and S. D. Jacobsen, *Thermal conductivity of lower mantle minerals*, Phys. Earth Planet. Inter., 174, 24-32, 2009.
- Liang, Q., C. Y. Chin, J. Lai, C. S. Yan, Y. F. Meng, H. K. Mao, and R. J. Hemley, *Enhanced growth of high quality single crystal diamond by MPCVD at high gas pressures*, Appl. Phys. Lett., 94, 024103, 2009.
- Sun, L., W. Yi, L. Wang, J. Shu, S. Sinogeikin, Y. Meng, G. Shen, L. Bai, Y. Li, H. K. Mao, and W. L. Mao, *X-ray diffraction studies and equation of state of methane at 200 GPa*, Chem. Phys. Lett., 473, 72-74, 2009.
- Wang, L., Y. Pan, Y. Ding, W. Yang, W. L. Mao, S. V. Sinogeikin, Y. Meng, G. Shen, and H. K. Mao, *High-pressure induced phase transitions of Y2O3 and Y2O3:Eu3+*, Appl. Phys. Lett., 94, 061921, 2009.
- Wang, L., Y. Ding, W. Yang, W. L. Mao, W. Liu, Z. Cai, J. Shu, G. Shen, and H. K. Mao, *Application of nano/submicron-focused x-ray probe for ultrahigh-pressure studies*, High Pressure Synchrotron Science Workshop (Argonne, IL, May 6-8, 2009).
- Zeng, Q. S., Y. Ding, W. L. Mao, W. Luo, A. Blomqvist, R. Ahuja, W. Yang, J. Shu, S. V. Sinogeikin, Y. Meng, D. L. Brewe, J. Z. Jiang, and H. K. Mao, *Substitutional alloy of Ce and Al*, Proc. Nat. Acad. Sci., 106, 2515-2518, 2009.

- Liang, Q., C. S. Yan, Y. Meng, J. Lai, S. Krasnicki, H. K. Mao, and R. J. Hemley, *Recent advances in high-growth rate single-crystal CVD diamond*, "Diamond and Related Materials", Volume 18, Issues 5-8, May-August 2009, Pages 698-703
- Liang, Q., C. S. Yan, Y. Meng, J. Lai, S. Krasnicki, T. Yu, H. Shu, H. K. Mao, and R. J. Hemley, *Ultratough single crystal diamonds by MPCVD*, Proceedings of Intertech 2008, submitted.
- Liang, Q., C. S. Yan, Y. Meng, J. Lai, S. Krasnicki, T. Yu, H. Shu, H. K. Mao, and R. J. Hemley, *Ultratough boron-doped CVD single-crystal diamond*, Adv. Mat., submitted.
- Liang, Q., C. S. Yan, Y. F. Meng, J. Lai, S. Krasnicki, H. K. Mao, and R. J. Hemley, *Enhancing the mechanical properties of CVD single-crystal diamond*, "Journal of Physics: Condensed Matter", Issue 36, 9 September 2009.
- Liang, Q., C. S. Yan, Y. F. Meng, J. Lai, T. Yu, H. Shu, S. Krasnicki, H. K. Mao, and R. J. Hemley, *Evidence for ultratough single crystal CVD diamond*, Phys. Stat. Sol., in press.
- Beck, P., A. F. Goncharov, J. A. Montoya, V. V. Struzhkin, B. Militzer, R. J. Hemley, and H. K. Mao, *Response to "Comment on 'Measurements of the thermal diffusivities at high-pressure using a transient heating technique'"*, "Applied Physical Letters, Volume 95, Issue 9, August 2009.
- Beck, P., A. F. Goncharov, V. V. Struzhkin, B. Militzer, R. J. Hemley, and H. K. Mao, *Measurements of thermal diffusivity under pressure in the diamond-anvil cell*, Appl. Phys. Lett., to be submitted.
- Beck, P., A. F. Goncharov, H. K. Mao, and R. J. Hemley, *High pressure and temperature Raman spectroscopy of olivine*, Geophys. Res. Lett., in preparation.
- Zha, C. S., S. Krasnicki, Y. F. Meng, C. S. Yan, J. Lai, Q. Liang, H. K. Mao, and R. J. Hemley, *Composite chemical vapor deposition diamond anvils for highpressure/high-temperature experiments*, "High Pressure Research", Volume 29, Issue 2, June 2009.
- Somayazulu, M., A. Levedahl, S. Gramsch, H. K. Mao and R. J., Hemley, *High pressure-temperature Raman spectroscopy of C2 clathrate* of H_2- H_2O*: Melting studies to 40 GPa and 1000 K*, J. Phys. Chem., in preparation.

Statement by the Prizewinners and by Patti Barkett:

We are especially pleased by the Foundation's focus on training the next generation of researchers. The Accademia del Cimento was closed after only a decade of existence, despite its magnificent productivity. In our own times the quest for understanding likewise encounters periods of difficulty if not darkness. In a span

of ten short years, the Accademia lit a spirit of inquiry that became a touchstone for modern science. Visionary institutions like the Balzan Foundation celebrate and preserve this noble tradition. Thank you once again. Russell J. Hemley and Ho-kwang Mao (Berne, 11.11.2005)

She enjoyed her science research lab experience at the Geophysical Laboratory, Carnegie Institute of Washington D.C. very much this year. She is so grateful to the Balzan Foundation and their support for young scientists, like herself, who are curious and passionate about discovering new things. Dr. Stephen Gramsch, research scientist at the Geophysical Laboratory in charge of her Balzan High School Fellowship project, was such an inspiration and allowed her to experience research like a "real scientist". She is even more committed, now, to pursue her passion in science. Priceless! (Patti Barkett, Claire Barkett's Mom, 2009)