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Russell J. Hemley and Ho-kwang Mao

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Motivation for the Balzan Prize and *laudatio*

To Russell J. Hemley and Ho-kwang Mao 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.

Russell J. Hemley and Ho-kwang (Dave) Mao have tackled, for the last twenty years of their joint research, some of the fundamental questions in Mineral Physics. One of them is to understand the behavior of materials at high pressure. They have developed numerous techniques, including the invention and perfection of synchrotron methods as well as a variety of spectroscopy techniques that have become standards in the field since the 1990s.

They have extended some of their techniques to examine the most abundant "mineral" in the universe, hydrogen, under conditions of extreme pressure to find new states of hydrogen that have transformed our understanding of this fundamental material.

Calculations on deep Earth mantle phases combined with experiments including the first spectroscopy measurements culminated in new models for the Earth's interior. Specifically, that research has led to results that have changed our views on the deep mantle, especially the core-mantle boundary region.

Their work has also had an impact on our understanding of the elastic anisotropy and super-rotation of the Earth's core, the enigmatic trapping of volatiles in the Earth and the existence of novel extraterrestrial minerals. Their research has thus contributed to a better knowledge of the chemistry and physics of the Earth's mantle and core.

Their results have provided a fundamental basis for the understanding of the interiors of large planets, including those found outside the solar system. Moreover, their work has led to discoveries beyond mineral physics in condensed matter physics, chemistry and materials science. These findings include the existence of novel high-pressure superconductors, superhard materials, new classes of molecular compounds, and high-density amorphous materials.

Because of the deep and broad impact of Hemley-Mao's work, their leadership in the field and their highly innovative research, they are worthy recipients of the Balzan Prize for Mineral Physics.

Résumé of Research
by Russell J. Hemley and Ho-kwang Mao
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The research of Russell J. Hemley and Ho-kwang Mao is driven by the quest to understand the nature of materials under extreme conditions of pressure and temperature. Their work has led them to investigate a broad spectrum of materials – from the simplest and most abundant elements in the cosmos, to the complex and inaccessible materials residing deep within planets, to systems at the interface between the organic and inorganic world, to entirely new and useful materials created under pressure. The following summarizes aspects of their joint research within the context of developments in a variety of fields in the physical and biological sciences.

The Advent of Mineral Physics

At the core of this research is mineral physics, a field in which the thermodynamic variables of pressure and temperature play a central role. The origins of the field may be traced to the advent of experimental science in the 17th century and the later emergence of geology as a discipline. In the early years of the 20th century, Erskine Williamson and Leesom Adams of the Carnegie Institution led the development of high-pressure studies of minerals and the application of mathematical physics to understanding the Earth's interior.[1,2] In 1936, John D. Bernal suggested that seismic discontinuity at 400 km depth arises from the olivinespinel transition in $(Mg,Fe)_2SiO_4$.[3] Later, Francis Birch's profoundly influential paper (1952) laid out the paradigm for interpreting the constitution of a planet from its crust to its core, in terms of pressure- and temperature-induced changes in candidate materials.[4] But mineral physics came into its own with the advent of the plate tectonic revolution in the middle of the last century, when it became clear that forces deep within the Earth drive large-scale processes of the planet as a whole.[5] Hence the behavior of the materials at depth underlies global processes of which the movements of plates are merely the surface expression. Understanding this broad range of materials phenomena has been the goal of mineral physics. The term itself is largely due to the efforts of Peter M. Bell and Charles T. Prewitt (USA), S.S. Hafner (Germany) and Arnold S. Marfunin (USSR) in the 1970s.[6] Indeed, one of the primary aims of modern mineral physics has been to supply the missing link between the global and the atomic – how planetary structure, dynamics, and evolution are controlled by the fundamental physical and chemical properties of the component materials, and not just for the Earth but also for all bodies in the solar system and beyond. The field of mineral physics not only supplies that link, it has also established entirely new avenues of research. An array of transformations in solids, liquids, and gases under the extreme pressure-temperature conditions of deep planetary interiors have been discovered, thus identifying the "brave, new world" of materials within planets, which is utterly different from that observed at or near planetary surfaces. Detailed *in situ* measurements of the physical and chemical properties of a broad range of relevant materials have been carried out up to the pressures found at the center of the Earth (3.6 Mbar). These measurements have revealed new bonding, electronic, magnetic and structural states in materials, requiring the extension of established precepts developed in the early years of quantum mechanics by Linus Pauling[7] and Eugene Wigner and Frederick Seitz.[8] Due to pressure-induced changes in chemical affinities, the reactivities of otherwise familiar elements and compounds are totally altered, and entirely new classes of materials appear. For organic materials, these changes occur at very modest pressures, with results that have major implications for life in extreme environments elsewhere in the solar system. At combined high pressures and temperatures, novel electronic and structural properties emerge, creating new phases that can be recovered to ambient conditions. Indeed, understanding the broad spectrum of phenomena exhibited in simple molecular systems up to multimegabar pressures and from the millikelvin range to the highest temperatures goes to the core of our understanding of materials.[9]

Professional Background

In 1964, Mao started his Ph.D. thesis work at the University of Rochester, using the diamond-anvil cell for studies of mantle minerals under the guidance of William A. Bassett and Taro Takahashi. In 1968, he joined the Geophysical Laboratory, a world-leading high-pressure center, for post-doctoral work on crystal-field spectroscopy of lunar and terrestrial minerals with Peter M. Bell, himself a student of Francis Birch and Percy W. Bridgman, recipient of the 1946 Nobel Prize in Physics for his contribution to high-pressure research. At Carnegie, Mao broadened his expertise and began to utilize other high-pressure devices such as the hydrothermal bomb, Birch gas apparatus, Bridgman squeezer, piston-cylinder apparatus and the tetrahedral press. At that time, the frontiers of static compression, including the Drickamer cell, the Bridgman anvils and the diamondanvil cell, were limited by the ceiling of verifiable pressure of 300-400 kbar. Multimegabar pressures had been claimed with diamond indenters and the split-sphere apparatus, but quantitative sample characterizations, including pressure measurements, were not conducted with these instruments.

Driven by the need to reach higher pressures in the laboratory equivalent to those of the deep mantle and core, Mao and Bell mounted a ten-year effort to extend the range of the diamond-anvil cell to more extreme conditions and to integrate the device with microscopic X-ray and laser-optical probes for *in situ* measurements on samples as well as accurate determination of pressure. The ruby scale calibrated at that time has been used as a universal standard ever since. With the Mao-Bell cell, they reached 0.5 Mbar for deep mantle studies in 1975, broke the 1 Mbar barrier and approached the core-mantle boundary pressure in 1976. They then went beyond 2 Mbar and well into the pressure range of the Earth's core in 1984, and proceeded to the pressure of the planet's very center in 1986. Using the newly acquired capabilities, they systematically investigated phase relations and equations of states of major minerals in the lower mantle and core, and started high-pressure investigations of gases and ices at conditions of Jovian planetary interiors.

Hemley entered the field of mineral physics from chemical physics in 1984. The son of a geologist, he was exposed to Earth science early in life and pursued his bachelors and masters degrees in chemistry. After completing a Ph.D. thesis in molecular spectroscopy and quantum chemistry, he did post-doctoral work in theoretical mineral physics with Professor Roy Gordon at Harvard. His first work brought techniques of theoretical chemistry and condensed-matter theory to mineral physics, as part of a broader movement at that time to bring mineral physics to the same level of sophistication as other areas of physics. The need to test theoretical predictions brought Hemley to the Geophysical Laboratory to work with Bell and Mao, where he saw opportunities for contributing insights and techniques from modern physics and chemistry. Mao and Hemley launched new lines of experimental and theoretical research that impacted a range of problems and materials in mineral physics. The research program has resulted in approximately 335 papers that they have published together to date, a selection of which are highlighted below.

Dense Hydrogen: The Most Abundant "Mineral"

Hemley and Mao's work has led to a series of discoveries concerning dense hydrogen, the most abundant mineral in the visible universe. Vitaly L. Ginzburg, the Russian theoretical physicist and 2003 Nobel Laureate, termed the behavior of hydrogen at high pressures as one of the "Key Problems of Physics and Astrophysics" in his seminal book by that name.[10] Indeed, just as the development of the theory of first the atom[11] and then the chemical bond[7] began with hydrogen, our understanding of materials at high density, including the constituents of planetary interiors, must begin with proper understanding of hydrogen at very high compression, as described in the classic 1935 paper on metallic hydrogen by Eugene Wigner and Hilliard B. Huntington.[12] Hemley was led to this problem by two pre-eminent mentors at Harvard, Martin Karplus (Pauling's last graduate student) and Dudley R. Herschbach (1986 Nobel Laureate in Chemistry).

Their initial studies led immediately to the first experimental observations and measurements of hydrogen at megabar pressures [*Phys. Rev. Lett.* 55, 99 (1985)]. This was followed by discoveries of several transformations, and key aspects of the system were characterized, as summarized in approximately 100 experimental and theoretical papers with numerous collaborators [see *e.g.*, *Rev. Mod. Phys.* 66, 671 (1994)]. This work included the first very high-pressure X-ray measurements on hydrogen, the first experiments at megabar pressures, determination of sound velocity in dense hydrogen, determination of the high-pressure dielectric properties, optical observations at multimegabar pressures, high-pressure electrical conductivity of the material and, most recently, the first static high pressure-temperature measurements above 1000 K and 1 Mbar. These studies continue to this day.

The most crucial discovery was that of the major transformation in hydrogen at 1.5 Mbar [*Phys. Rev. Lett*. 61, 587 (1988)]. This was unexpected and led to numerous subsequent studies of hydrogen around the world, including a systematic series of experimental and theoretical investigations. These studies revealed, for example, that the phase diagram of hydrogen and its isotopes is extraordinarily rich. With increasing pressure, the materials undergo a series of transitions, starting with pressure-induced ordering of the freely rotating molecules of the solid first identified by Pauling in 1930,[13] and culminating in structures in which the molecules strongly interact and exhibit an unusual combination of quantum and classical properties [*Phys. Rev. Lett.* 78, 1066 (1997)]. New phenomena were uncovered, particularly at low temperatures.

Realizing the value of synchrotron radiation for studying hydrogen under pressure, the team directed the development of new techniques for infrared spectroscopy of materials at megabar pressures [*Phys. Rev. Lett.* 69, 1129 (1992)]. This work led to the remarkable discovery of the charge-transfer state in the material, as evidenced by the enhancement of the infrared intramolecular stretching mode [*Phys. Rev. Lett.* 70, 3760 (1993); *Nature* 369, 384 (1994)]. This has been the subject of studies by numerous theoretical calculations by leading condensed matter theory groups around the world.[14-18] Synchrotron infrared techniques indicate no evidence for band-gap closure at the onset of the major 1.5 Mbar transition, and this provided new upper bounds to be placed on the optical conductivity at higher pressures within the phase [*Phys. Rev. Lett.* 76, 1667 (1996)]. However, the band gap is small at these pressures [*e.g.*, *Nature* 35, 488 (1991)], indicating that thermal excitations at high temperatures could give rise to the metallic conductivity observed for the shock compressed fluid at these pressures (at ~3000 K) [*Nature* 380, 671 (1996)].[19]

Spectroscopic studies indicate that the atomic transition in the solid must occur above 3.0 Mbar, where optical changes are observed [*Science* 244, 1462 (1989); *Rev. Mod. Phys.* 66, 671 (1994)]. Recent work in other labs have confirmed and extended these early results. [20] At the same time, a wealth of exciting new questions have arisen, including the behavior at high temperatures and at very low temperatures, as well as at much higher pressure (>3 Mbar).[21]

One of the holy grails of dense hydrogen, determining the structure at high pressure by X-ray diffraction – said to be an impossible measurement by many – was reached using synchrotron X-ray diffraction techniques [*Science* 239, 1131 (1988)]. These methods were subsequently brought to a larger synchrotron facility to obtain the structure above one megabar (1.20 Mbar) with colleagues in France [*Nature* 383, 702 (1996)]. This work showed that the crystal structure remains hexagonal and close-packed, and the material is more compressible than was expected from theory and lower pressure measurements. The results have been combined with higher pressure theoretical calculations for incorporation in general equation-of-state models for hydrogen, which are crucial for planetary and fusion applications. The new phase that appeared at 1.5 Mbar was thus found to be one in which the molecules strongly interact in an unexpected chargetransfer state, which generated considerable interest in theoretical physics and spawned a large number of calculations, including those carried out with the Carnegie group [*Phys. Rev. Lett.* 67, 1138 (1991)]. Multiple invariant points (*e.g.*, critical or tricritical points) on the phase line were observed, all of which were unexpected. The surprising behavior of the ortho-to-para conversion rate was discovered in measurements carried out by college intern Eran Karmon, and these results were explained theoretically in a paper co-authored by Mikhail Strzhemechny [*Phys. Rev Lett.* 85, 5595 (2000)]. Detailed measurements of the excitations in ortho-para mixed crystals showed such phenomena as Anderson localization [*Phys. Rev. Lett.* 74, 1379 (1995)]. Subsequent work has focused on the combined high-pressure/high temperature properties of hydrogen as they relate to conditions within the interiors of the large gaseous planets [*Phys. Rev. Lett.* 90, 175701 (2003)].

These results have had important implications for condensed matter theory. The molecular bonding state persisted over a factor of ten higher in terms of pressure than the original predictions of Wigner and Huntington (which claimed a transition at 250 kbar). Moreover, in this higher pressure regime, a wealth of phenomena such as the 1.5 Mbar transition were unanticipated. The reason for this unexpected behavior was straightforward. Despite the putative simplicity of the hydrogen atom – with one electron and one proton – accurate theoretical calculations for an ensemble of hydrogen atoms pose a particular challenge to conventional condensed-matter theory.[22] This difficulty arises from the quantum character of the atomic nuclei (zero-point energy) associated with their low mass, which requires the proton and electron dynamics to be treated on the same theoretical footing.[23,24] The wealth of experimental data that emerged from these studies has therefore provided a rich test bed for the further development of bonding and electronic structure theory, which can then be applied to the rest of the Periodic Table. As these methods have been refined in order to understand these data, new predictions have emerged. For example, subsequent extensions and applications of these theoretical approaches calibrated against data from their lab have given rise to suggestions of remarkable new phenomena, such as new types of electron pairing interactions, high-T_c superconductivity, and a superfluid ground state in the high-pressure metallic phase.[25-27]

Planetary Interior Models

As hydrogen is the most abundant "mineral" in the solar system, the experiments described above have provided a fundamental basis for the understanding of the interiors of large planets, including those found outside our solar system. Hemley and Mao also utilized these data to develop new interior models. The 1995 NASA Galileo probe of the Jovian atmosphere provided the first *in situ* measurements on composition, and the observations of the impact of the Shoemaker-Levy comet in 1994 made available a wealth of new observational data to compare with the experimental high-pressure data relevant to the richness of Jovian interior with depth. The first measurements of the velocity of sound in fluid and crystalline hydrogen were made as a function of density. The data were then used in a generalized model for the molecular layer of Jovian planets. Jovian models adjusted to reflect the new data remain discrepant with reported free oscillation spectra for the planet [*Science* 263, 1590 (1994)]. As pointed out in a follow-up paper [*Science* 269, 1233 (1995)], the reported seismic observations were shown to be invalid, as later studies also showed. There is now an effort to extend the sound velocity measurements to combined high-pressure-high temperature [*Phys. Rev. Lett.* 90, 175701 (2003)]. Prior to the experiments described above, this information was relegated to guesswork – that is, it essentially consisted of interpolating from low-pressure data over a vast range of compression to the Thomas-Fermi limit at extremely high density.[28]The information obtained from the new generation of experiments now underpins a new generation of experimentally based planetary interior models.[29]

These data are now a key component of models of the interiors of the gaseous and icy planets. Moreover, these high-pressure data have taken on a new importance with the discovery of numerous extrasolar planets. An effort is being mounted to extend these measurements to stellar interior conditions with new classes of experiments carried out with very large laser facilities. This work will bring about new linkages and interfaces among mineral physics, atmospheric science, condensed-matter physics, plasma physics and nuclear physics.

Silicate Perovskite and the Earth's Deep Mantle

Hemley carried out some of the first *ab initio* model calculations on magnesium silicate perovskite, now believed to be the most abundant mineral in the Earth, and other deep mantle phases. He began this work as a post-doctoral fellow in theoretical chemistry at Harvard and continued it at Carnegie in the mid 1980s. The theoretical work was then combined with – and helped drive – an experimental program with Mao that included the first spectroscopy measurements on silicate perovskite under pressure [*Silicate Perovskite,* (1989), p. 35] and the first measurement of the crucial pressure-volume-temperature equation of state in the 1990s [*J. Geophys. Res.* 96, 8069 (1991)], then one of the most important problems in mineral physics. The work culminated in a model for the Earth's interior involving weak compositional changes with depth and stratification of the upper and lower mantle [*Science* 257, 1099 (1992)]. The new level of understanding of silicate perovskite was summarized in a review written with Ronald E. Cohen [*Ann. Rev. Earth Planet. Sci.* 20, 553 (1992)]. Subsequent study of the element partitioning indicated a change in iron composition with depth within the lower mantle [*Science* 278, 2098 (1997)].

Most recently, the team has focused attention on the so-called post-perovskite phase of $(Mg,Fe)SiO_3$ [*Proc. Nat. Aca. Sci.* 101, 15867 (2004)]. This new phase was identified near 1 Mbar in experiments carried out in Tokyo by Kei Hirose using high pressure-temperature techniques the latter brought to Japan after a post-doctoral fellowship in their lab in the late 1990s. The Carnegie team discovered that the material has a very wide range of stability and can contain significant amounts of Fe. The observations are particularly important because the material is thus the "inner liner" of the silicate portion of the planet in contact with the hot dense fluid core. The physical and chemical properties also resolve a number of paradoxes regarding seismic anomalies in Birch's *D*" region and the core-mantle boundary. These observations have changed our views of the deep mantle, especially the core-mantle boundary region.

Transformations in Silica

Early on in their collaboration, Hemley and Mao focused on the high-pressure polymorphism and phase diagram of SiO_2, a system central not only to high-pressure mineralogy but also to condensed-matter physics and materials science. The modern experimental era of mineral physics began with the synthesis of stishovite in 1961 by Sergei M. Stishov and Svetlana V. Popova,[30] and its subsequent discovery in nature at Meteor Crater, Arizona, by Edward C.T. Chao and co-workers.[31] Influenced by James B. Thompson's suggestion that silica should transform to the much denser structure of rutile in the Earth's mantle (see Ref.[4]), as a young student Stishov carried out a series of high-pressure experiments that verified this prediction and electrified the world of geophysics, chemistry and solid-state physics. These experiments also opened the eyes of the scientific world to the central role of the pressure variable in mineral physics.

Although silica had been characterized to some degree in the intervening years, there was very little definitive information on its high-pressure properties, including compressibility, vibrational properties and higher pressure transformations. Hemley had calculated that a transition in stishovite should occur under pressure, and set out to measure the first Raman spectrum, working on synthetic and natural stishovite with Chao. The long-sought "post-stishovite" transformation was established. This work, carried out by their graduate student, Kathleen J. Kingma, documented the transformation from stishovite to the $CaCl_2$- type structure at 500 kbars by high-pressure Raman scattering [*Nature* 374, 243 (1995)] and single-crystal X-ray diffraction [*Solid State Commun.* 114, 527 (2000)]. A Landau theory analysis of the rutile-$CaCl_2$ transition was developed and used to evaluate the geophysical signature of free silica in the lower mantle [*J. Geophys. Res.* 105, 10807 (2000)]. This work thus established modern condensed matter theory as a route to making accurate and even quite subtle predictions about the high-pressure behavior of Earth materials. The work on silica was summarized in a review with Kingma and Prewitt [*Rev. Mineral.* 29 (1994), p. 41], which serves as an update on the Carnegie treatise on silica written by Robert Sosman and first published in 1927.[32] Hemley has continued a 20-year collaboration with Stishov, now the Director of the Institute where he discovered stishovite.

Amorphization, Glasses and Melts

The research on silica led to another discovery – that crystalline minerals can be transformed to types of glass by pressure. This pressure-induced amorphization was found by using the same spectroscopic techniques that had been applied to the original hydrogen problem at much higher pressures [*High-Pressure Research in Mineral Physics* 347 (1987)]. A related transformation had been observed previously in ice at low pressure and temperature.[33] Lattice dynamics calculations led them to understand this new class of transitions as associated with an elastic instability induced by compression. This was laid out in a subsequent paper using new synchrotron X-ray diffraction techniques applied to the problem [*Nature* 334, 52 (1988)].

Pressure-induced amorphization began to be reported in a broad range of materials, as other groups began to study the effect. A major problem in this work was associated with an inability to probe the materials over a sufficient range of length scales and with the lack of *in situ* techniques. This problem was solved in a series of microscopy studies carried out with Kathleen Kingma; these studies directly revealed the range of length scales associated with the transformation [*Science* 259, 666 (1993)], the existence of a metastable intermediate phase [*Phys. Rev. Lett.* 70, 3927 (1993)] and the complexity of the proposed glasses formed in this way [*Phys. Rev. Lett.* 72, 1302 (1994)]. The existence of an intermediate phase remained the subject of a great deal of subsequent theoretical papers by condensed matter theorists. Brillouin scattering measurements confirmed the elastic instability hypotheses for quartz specifically [*Phys. Rev. Lett.* 84, 3117 (2000)]. Pressure-induced amorphization is now documented in a broad range of materials; in addition to the novel dynamical aspects of the problem, it offers a new route for the synthesis of new materials with novel physical properties.[34]

The work on amorphization led to the discovery of new phenomena in related systems. The observation of amorphization of ice mentioned above had been reported using quench techniques. However, the transformation was not monitored directly; hence numerous questions remained with regard to the actual transformation, including its mechanism. Using newly developed *in situ* techniques, the transition sequence was directly observed and monitored by optical spectroscopy for the first time [*Nature* 338, 638 (1989)]. The study revealed the mechanism of the transformation, proof that the high-pressure phase was indeed amorphous and the pressure-temperature limits of high-density amorphous ice. Moreover, this exhaustive study revealed that this fundamentally important system – H_2O – is far richer than previously anticipated, revealing numerous new and unexpected transformations as a function of pressure and temperature. Aspects of this work were confirmed by others working in this field much later, including neutron studies carried out in the early 1990s,[35] as well as in very recent research.[36] In later work, another class of metastable transformations was revealed through these spectroscopic techniques [*Science* 281, 809 (1998)]. Together with the later higher pressure studies transformations discussed below [*Science* 273, 218 (1996); *Phys. Rev. Lett.* 78, 4446 (1997)], the work continues a tradition of study of the wonders of water and ice begun by Gustav Tammann[37] and Percy W. Bridgman[38] over a century ago.[39]

Related discoveries were made from studies of SiO_2. Work on H_2O pointed to the existence of high-density amorphous solids and the possibility of actual transformations between two different amorphous states. An obvious candidate for this was SiO_2 because of the noted isomorphism between H_2O and SiO_2 (both as tetrahedral network forming solids). This was a huge challenge experimentally because condensed-matter physicists had tried and failed to study (*e.g.*, by spectroscopy) silica glass, the archetypal glass that is both fundamentally and technologically important. In fact, very little had been done since Bridgman's study of the effect of pressure on the diffraction pattern of SiO_2 glass.[40] However, there was an even more important reason: the behavior of amorphous SiO_2 at high pressure is crucial for understanding the behavior of silica-rich melts in the mantle, and specifically for testing the revolutionary notion that such melts could achieve very dense states and therefore could be neutrally buoyant and entrained in the mantle. This property has enormous consequences for the evolution and dynamics of the Earth's interior because it allows melts, which chemically differentiate the planet, to compositionally and dynamically stratify the interior.[41]

The new high-pressure techniques that had been applied to hydrogen in ice were adapted to investigate this system, and they revealed that the structure changed in remarkable ways – there was an elastic change associated with the collapse of the distribution and angle of the Si-O-Si linkages, followed by an irreversible compaction at higher pressures arising from the redistribution of silica ring structures and a gradual increase in coordination of the silicon atom [*Phys. Rev. Lett.* 57, 747 (1986)]. The basic interpretation stands as the current paradigm by which compressional effects in silicate glasses and melts are now understood.[42] The work was followed by a series of other experimental studies, including the first X-ray diffraction measurements of silica glass under pressure [*Phys. Rev. Lett.* 69, 1387 (1992)] and the first X-ray study of an amorphous solid at very high pressures, which established the nature of the coordination change first proposed in silicate melts in the 1960s. This work also gave rise to numerous theoretical studies by their group and others. Notably, among these theoretical studies was the question of how octahedral coordination of the silicon was compatible with an amorphous or disordered state. This problem was solved in a first-principles theoretical study carried out with graduate student David M. Teter [*Phys. Rev. Lett.* 80, 2145 (1998)]. Most recently, the group has extended these studies to *in* *situ* neutron diffraction methods, including the very recent first neutron diffraction study of related transformations in GeO_2 [*Phys. Rev. Lett.* 93, 115502 (2004)]. *In situ* high-pressure investigation of amorphous solids and liquids is now an established field of research motivated by the search for new "polyamorphic" transitions and novel thermodynamic properties.[43]

Water and Ice

Water is ubiquitous on our planet, is essential for life as we know it, and in large measure controls the dynamics and evolution of planetary bodies. The low-pressure phase, normal ice I_h, is an abundant mineral on the planet's surface. Our understanding of the local structure of water and ice dates back to the seminal Bernal-Fowler-Pauling "ice" rules developed in the 1930s.[44],[45] The theoretically predicted transition of ice to a symmetric hydrogen-bonded (and therefore nonmolecular) phase in which the ice rules no longer hold was a classic problem in chemistry, physics, and mineralogy throughout the latter half of the last century. The first direct X-ray diffraction study of ice at megabar pressures established the basic structure of the material at 1.30 Mbar, while at the same time it resolved a number of theoretical inconsistencies regarding the compression curve [*Nature* 330, 737 (1987)]. In 1996, the group solved this 40 year-old problem by using synchrotron infrared and X-ray techniques [*Science* 273, 218 (1996)]. The X-ray measurements indicated that the oxygen sublattice remains body-centered cubic to at least 2.1 Mbar, with major changes in the infrared spectrum at 600-700 kbars, which identified the transition to the Cu_2O structure. Similar conclusions were reached on the basis of a lower pressure infrared absorption study carried out in Japan.[46] A wealth of new findings emerged from these studies, including an unprecedented cascading sequence of Fermi resonances[47] as a soft mode approaches the symmetrization transition, a Fano resonance[48] and an intermediate disordered state [*Phys. Rev. Lett.* 78, 4446 (1997); *Phys. Rev. Lett.* 83, 1998 (1999)]. The work led to a flurry of subsequent theoretical calculations and experimental studies around the world.[39] Most recently, Mao and Hemley's group has shown that the melting curve increases steeply at the transition to the symmetric hydrogen-bonded structure, indicating that symmetric hydrogen-bonded ice could be stabilized within the deep lower mantle of the Earth, a result with profound consequences for the hydrogen uptake in the Earth and the planet's internal dynamics [*Geophys. Res. Lett.* (2005)]. Specifically, it can explain the previously enigmatic increase in the viscosity in the middle of the lower mantle.[49]

Structure, Dynamics, and Evolution of the Earth

The discovery of major transformations in "volatiles" (liquids and gases), the pressure-induced chemistry discussed above, and the observation of new classes of dense hydrogen-rich minerals have had a dramatic effect on our understanding of the structure, dynamics and evolution of the Earth. The implications for the planet as a whole were articulated in a major review written with Quentin Williams [*Ann. Rev. Earth Planet. Sci.* 29, 365 (2001)]. The work extended the major element compositional models discussed above and provided an entirely new picture of the mechanisms of exchange of hydrogen between the deep interior and surface of the planet, as well as the means of retention and possible abundance of hydrogen deep within the Earth. The analyses indicated that the uppermost several hundred kilometers of the Earth's suboceanic upper mantle appear to be largely degassed, but significant primordial hydrogen could be retained within the transition zone, lower mantle, or core. Regassing of the planet occurs via subduction; cold slabs are likely to be particularly efficient at transporting hydrogen to depth. Marked changes in hydrogen cycling have taken place throughout Earth's history; evidence of hydrated ultramafic melts in the Archean and probable hydrogen retention within a Hadean magma ocean indicate that early in its history the deep Earth was substantially wetter. The core could represent the dominant reservoir of hydrogen on the planet, with up to ~100 hydrospheres of hydrogen present as a high-pressure iron-alloy.

Iron and the Earth's Core

Since the inner core was discovered in 1936,[50] it remained enigmatic for most of the 20th century. However, beginning in the late 1990s, geophysical observations revealed astonishing findings, including the observations of elastic anisotropy and possible super-rotation of the inner core. Understanding this in terms of materials seemed out of the question: elastic constants of iron had been measured to only a few kilobars; there was no information on texture; little information on the chemistry in the relevant phases of iron. Spectroscopy of iron even at ambient pressure seemed impossible. Moreover, it was becoming quite clear that the extrapolating ambient properties of iron at the extreme conditions expected at the Earth's center would provide no information.

The fact was that the key conditions of the Earth's core were unknown. Although the pressure was known precisely from modern geophysical observations (3.63

Mbar at the center, even from the early years), claims for the temperature at the Earth's center varied from 4500 to close to 8000 K, even through the 1980s. The key piece of information needed to settle this question was the determination of the melting temperature at multimegabar pressures because the temperature of the inner-core boundary must be where the iron alloy of the outer core freezes to form the solid inner core. In fact, determination of the melting curve of iron became an area of controversy in the field of mineral physics because the requisite techniques used in this work were in their infancy.

A systematic study of the Earth's core as a problem in experimental mineral physics was therefore launched in their group. Entirely new techniques to address the problem of the Earth's core from the point of view of the component "minerals" were developed. The melting curve of Fe to above 1 Mbar was directly measured, providing bounds on the temperature and density at the inner core boundary [*Phys. Earth Planet. Inter.* 143-144, 455 (2004)]. Techniques were developed and then applied to the strength [*Science* 276, 1242 (1997)], elasticity [*Phys. Rev. Lett*. 80, 2157 (1998)] and texture [*Nature* 405, 1044 (2000)] at core pressures. Hemley and Mao's student Sebastien Merkel measured the first vibrational spectrum of iron at core pressures [*Science* 288, 1626 (2000)]. The first measurements of the thermodynamic and elastic properties were measured using newly developed synchrotron inelastic scattering techniques [*Science* 292, 914 (2000)], which brought together experiment and theory. For example, observation of a strong lattice strain anisotropy in iron indicates a large seismic anisotropy, and therefore a perfect alignment of crystals may not be needed to explain the seismic observations. This work culminated in a review (2001) which defined the broad range of this new understanding of the Earth's outer and inner core [*Internat. Geol. Rev.* 43, 1 (2001)]. These experiments have spawned numerous related studies around the world. In short, for the first time since the proposed existence of the Earth's core, this once inaccessible and enigmatic region is now a problem in experimental science.

New Chemical Reactions in the Earth

A central finding of high-pressure mineral physics is that the behavior of materials within planets can be far different from what is thought, based on the familiar principles developed from knowledge of substances found at the surface.

The work on hydrogen naturally led to an effort to understand the nature of hydrogen in minerals, work that in turn led to several key discoveries that helped to establish the existence of new classes of minerals – dense hydrogen phases. The first of these discoveries was the high-pressure stability of iron hydride [*Science* 253, 421 (1991)], the first *in situ* high-pressure observation of the reaction between iron and hydrogen.

This work led to the exploration of new chemistry in the rare-gas solids under pressure, which was made famous by Neil Barlett in the early 1960s. Already, new Xe compounds have been discovered. Here an effort has been made to go beyond "van der Waals" chemistry, to open up an entirely new realm of synthetic inorganic chemistry, as in the discovery of the high-pressure stability of metal hydrides and nitrides discussed above. Indeed, profound changes in Xe under pressure were documented, including the first observations of structural transformations [*Phys. Rev. Lett.*59, 22670 (1987)]. Work performed with visiting scientist Mikhail Eremets demonstrated by direct measurements of electrical conductivity that Xe becomes metallic at 1.5 Mbar [*Phys. Rev. Lett.* 83, 2797 (2002)]. Thus major changes in chemistry are expected. This work included new high-pressure Xe compounds formed with H_2O as well as SiO_2 [*Proc. Nat. Acad. Sci.* 99, 25 (2002)].

A subsequent study was directed towards the possibility of methane generation in the mantle. *In situ* high pressure-temperature Raman, X-ray and optical microscopy documented the production of methane and other hydrocarbons from mineral phases at upper mantle conditions [*Proc. Nat. Acad. Sci.* 101, 14023 (2004)]. This work, spearheaded by post-doctoral fellow Henry Scott, has thus demonstrated that hydrocarbons can be synthesized abiogenically deep within the Earth. Whether this source contributes to petroleum reserves remains a major question. The results do support the controversial proposal of Thomas S. Gold of the existence of a hot, deep biosphere buried deep within the planet.[51] As Freeman Dyson wrote, "If the answer turns out to be inorganic, this has huge implications for the ecology and economy of our planet as well as for the chemistry of other planets." One of the striking findings here is that these perturbations can occur at very modest conditions.

Biology and Geobiology

A very new thrust area involves the study of organic systems under high pressure-temperature conditions as related to understanding the origin and evolution of life in extreme environments. Hemley's Ph.D. thesis addressed the electronic structure and dynamics of conjugated hydrocarbons as biological chromophores. In recent years, the team has begun to explore the interface between mineral physics and biology. Work spearheaded by post-doctoral fellows Anurag Sharma and James Scott led to the astonishing discovery that life can persist in the tens of kilobars pressure range (*i.e.*, as high as 16 kilobars) [*Science* 295, 1514 (2002)]. This work utilized techniques developed to study the inorganic materials described. The findings have resulted in a revision of our understanding of the limits of life under extreme conditions, and expanded the potential habitable zone in the solar system (*e.g.*, in the planetary moons Europa and Titan). Moreover, the work has demonstrated that these techniques provide an entirely new way in which to study the effects of stress on the adaptation of evolving microbial communities – in effect, studying "evolution" in a test tube [*Chemistry Under Extreme Conditions*, p. 83 (2005)]. The work has been the driver for new high-pressure structural studies of biological systems (*e.g.*, proteins and viruses) at synchrotron facilities. But this is just the tip of the iceberg, as the genomic and proteomic bases for these observations has not yet been examined. This is possible, however, by using the new generation of high-pressure analytical techniques that have been developed in their lab. Indeed, these new high-pressure microbiology experiments may eventually open up entirely new disciplines of high-pressure genetics and molecular biology.

Novel Transformation in Molecular Systems

Over seventy years ago, J.D. Bernal proposed that all materials must become metals if compressed under sufficiently high pressures, a proposal with profound implications for the sequestering of high-density phases within planetary cores. However, only recently has the full appreciation of this prescient conjecture been realized. In 1985, using techniques that they had just developed to study hydrogen at megabar pressures [*Phys. Rev. Lett.* 85, 1262 (1985)], the group showed that nitrogen transforms to an unusual opaque solid at pressures near 1.5 Mbar at room temperature compression.[52] Armed with the recently developed techniques, they returned to this problem during the late 1990s and discovered a wide range of phenomena. Using highly sensitive Raman techniques, synchrotron infrared spectroscopy and chemically ultrapure synthetic diamond anvils, clear evidence for the transition to the non-molecular form was found at the expected pressure of the earlier work (1.50 Mbar) [*Phys. Rev. Lett.* 85, 1262 (2000)]. This spectroscopic study was followed by direct electrical conductivity measurements that revealed that the material is a non-diatomic semiconductor to at least 2.40 Mbar [*Nature* 411, 170 (2001)]; the excellent degree of agreement with theory is heralded as one of major achievements in modern condensed-matter theory. Moreover, at lower pressure, new phases were also found that indicate that the phase diagram of the molecular material is in fact quite different. New strongly interacting phases have spawned the development of new theory.[53] These phases are potentially useful energetic materials, as are other nitrogen-containing materials subjected to these conditions.

Related polymerization transformations have subsequently been observed by other groups in other systems (*e.g.*, CO_2 [54] and H_2CO_2 [55]). The first *in situ* high pressure-temperature spectroscopic measurements on volatiles such as CO_2 at mantle conditions established the stability fields of new phases. Using new *in situ* X-ray diffraction techniques, the longstanding controversy regarding the phase diagram of sulfur[56] was resolved [*Nature Materials* 4, 152 (2005)]. The phase transition sequence, first in its non-metallic phases and then in the high-pressure superconducting state, demonstrated that it is very different from what has been previously reported or assumed.

One of the most unexpected and exciting developments in high-pressure mineral physics was the discovery of the ordered alloys of molecular materials. The first example was $(N_2)_{11}$, which Hemley found with their post-doctoral fellow Willem L. Vos [*Nature* 358, 46 (1992)]. They named this new class of materials “van der Waals” compounds, by analogy to weakly bound molecules observed in the gas phase. Remarkably, these molecular compounds had structures identical to those found in a very different class of materials, metal alloys. Subsequent study of these novel materials has revealed an unexpected richness that was unanticipated theoretically, and these results were then observed in other labs around the world.[57] Meanwhile, the work in Hemley and Mao’s lab continued to lead to new findings. Post-doctoral fellow Maddury Somayazulu discovered up to six molecular compounds in the CH_4-H_2 binary system, all at pressures below 80 kbars [*Science* 271, 1400 (1996)]. These new stoichiometric compounds have been shown to exhibit unexpected properties at very high pressures, such as an unusual infrared response indicative of the evolution of a van der Waals to a charge transfer (or ionic) state.

The discovery of dense clathrates or filled ices, first observed in hydrogen-water mixtures [*Phys. Rev. Lett.* 71, 3150 (1993)] has opened up new lines of research. These novel structures may host trapped gases within the moons of the solar system (*e.g.*, in the CH_4-H_2O system) [*Properties of Earth and Planetary Materials at High Pressure and Temperature*, 1998, p. 173].[58] Subsequent studies have shown that hydrogen remains trapped in ice below ambient pressure [*Science* 297, 2247 (2002)]. Moreover, the infrared spectra matches what is found in certain interstellar clouds, suggesting a mode of hydrogen incorporation in growing planetary bodies. Together with high-pressure van der Waals compounds, these dense molecular materials may be abundant in the molecular layers in extraterrestrial bodies, including surfaces and interiors of moons in the outer solar system – pointing to a new type of extraterrestrial mineralogy. New high-pressure phases in gas hydrates discovered in the methane-water system at even modest pressures of a few kilobars suggest that much of the methane clathrate buried deep in sediments in the Earth may exist in a different crystal structure than what has been observed on recovery [*Proc. Nat. Acad. Sci.* 97, 13484 (2000)]. Studies of these systems provide an opportunity to investigate the evolution of bonding from purely van der Waals to ionic-covalent on compression and provide an entirely new window on the nature of the chemical bond [*Ann. Rev. Phys. Chem*. 51, 763 (2000)].

Very recently, these materials have become extremely interesting hydrogen storage materials because of their high hydrogen content and "green" chemistry (simply hydrogen gas and water). The low-pressure H_2-H_2O clathrate contains 5.4% hydrogen and therefore meets the U.S. Department of Energy 2005 milestone for a useful hydrogen storage material. The material has been patented and is being pursued by industrial and other research groups.[59] Moreover, the $(H_2)_4(CH_4)$ phase has an astonishingly high hydrogen content of 33.4%, the highest of any known hydrogen containing material, and it can be stabilized near ambient pressure at low temperature [*Chem. Phys. Lett.* 402, 66 (2005)]. Like the polymerization studies of molecular materials, these discoveries are examples of the societal benefits of fundamental research in high-pressure mineral physics [*Rev. Mineral. Geochem*. 41, 335 (2001)].

New Superhard Materials: Large Single Crystal Diamond

One of the dreams of materials science is to produce a substance that is harder and stronger than nature's most renowned mineral, the diamond. Indeed, here the ideas of mineral physics have played a critical role. In the early 1990s, based on first-principles calculations, Marvin L. Cohen at Berkeley suggested that carbon nitrides in one of the structures of silicon nitride could be such a material. Working with graduate student David M. Teter, he showed that the previously proposed structure was in fact unstable. Moreover, using crystal chemical arguments based on analogies to high-density silicate structures, they theoretically found a new class of higher density structures with even higher stiffnesses [*Science* 271, 53 (1996)]. The proposed class of materials, which was patented in 1999, has led to a worldwide effort to fabricate these new carbon nitrides. Analyses of the physical properties of dense materials have provided a means to predict the existence of new superhard phases [*Phil. Mag. A* 82, 231 (2002)].

The effort to create new materials has recently led to new discoveries in entirely different regimes of pressure – the synthesis of large single crystals of diamond by chemical vapor deposition. This effort was driven by the need to develop very large and more perfect diamonds for high-pressure experimentation. In the early 1990s, Hemley and Mao began to force the limits of natural diamonds with the discovery of new transitions in diamond under pressure [*Nature* 351, 721 (1991)]. Shortly thereafter, they initiated a program with Yogesh Vohra to attempt to synthesize single diamond crystals by chemical vapor deposition (CVD). Their joint student, Chih-shiueYan, developed a technique for doing this [*Proc. Nat. Acad. Sci.* 99, 12523 (2002)]. Moreover, the single crystals are grown at rates that are in some cases 100 times faster than conventional processes, thus opening the prospect of producing very large (*e.g.*, >100 carat) diamonds quickly and efficiently for a broad range of applications. In addition, because of its high perfection but slightly different microstructure, the diamond produced at this high growth rate is initially tougher than natural diamond, and after annealing it is significantly harder [*Phys. Status Sol.* 201, 25 (2004)]. The work opens up the prospect of creating an entirely new generation of high-pressure experimentation for studying planetary interiors.[60] But the implications go far beyond this. These discoveries have the potential to revolutionize the diamond industry as well,[61],[62] most notably by helping to lay the groundwork for a new diamondbased high technology (*e.g.*, replacing silicon with diamond in electronics) of the 21st century.

New Superconductors

Hemley and Mao's interests in both pressure-induced electronic transitions and complex materials led them to the field of superconductivity. One of the important features of the perovskite-based high-T_c superconductors is their similarity to natural minerals. Indeed, the first syntheses of the minerals required the techniques of mineral physics for their characterization because of the polyphase nature of the material and the high degree of disorder. In fact, the condensed matter physics community was unable to characterize these materials when they were first synthesized because of their complexity, and they had to turn to mineral physicists (and in particular the group at Carnegie), who had the requisite microanalytical methods. As such, they were the first to measure the vibrational spectra of the 90 K superconductors [*Phys. Rev. Lett.* 58, 2340 (1987)], work that could not be duplicated in many condensed physics laboratories for several years because of the inability to accurately examine small polyphase samples. Following this publication, these labs obtained identical micro-optical instrumentation, and thus the effort played a useful role in the further characterization of the high-T_c superconductors.[63]

In the 1960s Alexis A. Abrikosov, the 2003 Physics Nobel Laureate, predicted that superconductivity would be enhanced in metals at high density,[64] and Neil W. Ashcroft calculated that the celebrated high-pressure metallic phase of hydrogen could be a very high-temperature superconductor,[65] as discussed above. With the advances already made in hydrogen, and with experience with high T_c materials, Hemley and Mao decided in the mid-1990s to begin direct studies of superconductivity in elemental systems – to test the general ideas of Abrikosov and as a stepping stone toward solid metallic hydrogen itself. This required, however, the development of altogether new experimental magnetic and electrical methods for quantitative measurements in minute samples at multimegabar pressures. To this end, they began a program to extend the technology developed at Stishov's Institute of High Pressure Physics in Troitsk with megabar diamond cell methods. This new initiative was highly successful and opened an entirely new area of research. Numerous elemental superconductors have been discovered, including sulfur [*Nature* 390, 382 (1997)], boron [*Science* 293, 272 (2001)] and lithium [*Science* 297, 1213 (2002)]. To date, some 23 elemental superconductors have been found at high pressure, increasing the number of known superconducting elements to 52. Like the work on dense hydrogen, the results are having a dramatic impact on condensed-matter theory.[66],[67] For example, the observations provide important insights into the possibility of new mechanisms of superconductivity that go beyond the conventional phonon-mediated Bardeen-Cooper-Schrieffer theory.[68] Motivating this burgeoning new area of research is the question of whether these new classes of superconductors provide evidence for new mechanisms of superconductivity (*e.g.*, as proposed for hydrogen).[25] This new and growing area of fundamental study is yet another example of the profound implications mineral physics studies have had on the broader physics and materials community, in this case, providing information crucial for advancing our understanding of fundamental aspects of condensed matter.

Technique Development

In the late 1960s and through the 1970s, Mao and Bell advanced a broad range of high-pressure techniques, culminating in the invention of the megabar diamond anvil cell and the attainment of static pressures well into the multimegabar pressures range, as discussed above.[69] This focus on technique development continued when Hemley joined the group, and this work led to the invention and perfection of numerous synchrotron and optical spectroscopic techniques [*Science* 237, 605 (1987)], methods that became standards in the field through the 1990s. They also pioneered the development and application of synchrotron infrared spectroscopy [*II Nuovo Cimento D* 20, 539 (1998)], which was essential for establishing the molecular-nonmolecular transformation in ice [*Science* 273, 218 (1996)] and the bounds on the metallization of hydrogen [*Phys. Rev. Lett.* 76, 1667 (1996)] described above. The development of electrical transport and magnetic measurements was pioneered with Mikhail Eremets, Viktor V. Struzhkin, Yuri A. Timofeev, and Takuo Okuchi. The laser heating methods that were developed are now in use worldwide, especially in Japan where many recent discoveries have been made.[70] The team is actively involved in the development of new synchrotron radiation methods, and they are developing the next generation of high-pressure neutron scattering instrumentation at new facilities under construction in the U.S. (*i.e.*, the world's most powerful facility, the Spallation Neutron Source at Oak Ridge National Laboratory). The fabrication of large single crystal diamond by CVD will be used to develop an entirely new generation of large volume diamond cells based on colossal diamonds. These new methods will be essential for a wide range of experiments, from microbiology studies at kilobar pressures to investigations of planetary cores at multimegabar pressures and thousands of degrees.

Indeed, for the first time, the latter high pressure-temperature experiments will offer the potential to overlap the range of conditions sampled in dynamic compression (shock-wave) studies, thus providing new tests of theory. Moreover, combined static and dynamic compression experiments will be possible, and they will access altogether new thermodynamic states, thus bridging the gap between mineral physics and astrophysics. There have been important advances in theoretical methods as well. Hemley's initial work in mineral physics involved the implementation of new theoretical and computational methods. The effort to advance the sophistication of theoretical mineral physics has exceeded the expectations of many. Owing to the complexity of mineral systems or "real materials" and the great importance of understanding their behavior under extreme conditions within the Earth, theoretical studies of mineral systems are just equal to – but in many ways are now leading – developments in condensed matter theory, as many condensed-matter physicists turn to mineral physics techniques and problems for study [*Ultrahigh-Pressure Mineralogy, Rev. Min.* 37, 1998]. Computational mineral physics is now a major activity at Carnegie and is led by Ronald E. Cohen, their long-term collaborator, and more recently Burkhard Militzer, one of the leading young theorists in the first-principles theory of hydrogen in large planets.

Education and Outreach

Scientific training has been central to this team's research. Indeed, the work would not have been possible without the constant input and collaboration of bright and enthusiastic young scientists. Together, Hemley and Mao have worked with over 80 post-doctoral fellows, research associates, and graduates, in addition to numerous college and high-school interns. Some 24 of their joint post-doctoral fellows and students have moved into faculty positions at major universities around the world. They are especially pleased that, during the past three years alone, twelve of them have obtained academic positions and have set up their own high-pressure laboratories. Others have important positions in government labs worldwide, or in industry, or they direct national policy. Of their many college interns, many have pursued graduate school in science and engineering. Several high school students have published major articles in high impact journals, and have won awards in national science contests. The two continue to promote mineral physics in other ways. In 1998, Hemley and Mao organized the highly successful short-course "Ultrahigh-Pressure Mineralogy," under the auspices of the Mineralogical Society of America. Participants from around the world were involved, and Hemley edited the course book, which remains a standard reference on high-pressure mineral physics [*Ultrahigh- Pressure Mineralogy, Rev. Min.* 37, 1998]. In 2001, he organized and ran the highly successful Enrico Fermi Summer School "High-Pressure Phenomena," in Varenna, Italy, in July 2001 (with Guido Chiarotti). Approximately 100 students were involved in this first course on this topic in the 50 year history of this world-famous summer school on Lake Como. He has also co-edited two other books, *High-Pressure Materials Research* in 1998, and *Physics Meets Mineralogy* (with Japanese scientists) in 2000. Mao and Hemley have worked to promote the field of mineral physics from its early years in the field, contributing to the 1986 *Earth Materials Research* Report edited by Charles T. Prewitt, which established the goals and priorities for the field in the United States through the end of the 1990s. They organized a successful symposium in 2000 "Mineralogy at the Millennium," which outlined a roadmap for the current decade and beyond [*Science* 285, 1026 (1999)]. Mao is Director of the U.S. high-pressure X-ray facility at Argonne National Laboratory (HPCAT), a U.S. national X-ray facility, and Hemley is the Director of a U.S. national high-pressure center (CDAC, the Carnegie/DOE Alliance Center), which is dedicated to the development of high-pressure science and technology, and the training of a new generation of students in high-pressure materials science, including mineral physics. Both have also been active in U.S. and international committees in mineral physics, and maintain collaborations with leading groups throughout the world.

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Balzan research project – abstract

New Directions in Mineral Physics: Multidisciplinary 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. 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.

The four-year project is focused on training and its goal is the exploration of the new pressure dimension in multidisciplinary physical sciences. The fellowships will encourage the development, design, and fabrication of new instrumentation that will exploit the CVD diamond technology developed by Hemley and Mao. Publications and further dissemination of results are also being financed.

In the first year, the funds were used to support talented young individuals ranging from the high school to the post-doctoral level from different parts of the world, giving them the opportunity to work with Hemley and Mao on projects opening new frontiers of high-pressure research.

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. Work to date has led to the first high pressure-temperature Raman studies of olivine and 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 just 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.
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 hy-

drogen 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.
In the second year, the Balzan Award funded research project will include high-pressure biology and Hemley and Mao have already identified several promising students who will work with them on this aspect of the project.
The following papers and abstracts have been published and/or are nearing completion.
- 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).
- 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, 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.
Somayazulu, M., A. Levedahl, A. Goncharov, H. K. Mao, and R. J. Hemley, High pressure-temperature Raman spectroscopy of H_2-H_2O clathrate, *Bull. Am. Phys. Soc.* (APS March Meeting) (Denver, CO, March 5-9, 2007).
- Somayazulu, M., A. Levedahl, S. Gramsch, H. K. Mao, and R. J, Hemley, High pressure-temperature Raman spectroscopy of C_2 clathrate of H_2-H_2O: Melting studies to 40 GPa and 1000 K, *J. Phys. Chem.*, in preparation.

Biographical and bibliographical data

Russell J. Hemley, born on 26 October 1954 in Berkeley, California, is a US citizen.

Since 1987, Senior Staff Scientist at the Geophysical Laboratory of the Carnegie Institution of Washington, of which he has been appointed Director, effective 1 July 2007. Since 2003 Director of the Carnegie/DOE Alliance Center (CDAC) and Associate Professor of the high-pressure instrument (SNAP) at Spallation Neutron Source at Oak Ridge National Laboratory.

He received his BA (1977) from Wesleyan University, his MA (1980) and his Ph.D. (1983) from Harvard University. After a post-doctoral fellowship in theoretical chemistry at Harvard (1983-1984), he became a Carnegie Fellow (1984-1986) and a Research Associate (1986-1987) at the Geophysical Laboratory. In 1987 he was appointed as a Staff Scientist at the Geophysical Laboratory, Carnegie Institution of Washington. He was Visiting Professor at the Johns Hopkins University (1991-1992) and at the École Normale Supérieure, Lyon (1996, 1999).

Among his honours and memberships in professional societies we would mention the Hillebrand Medal of the American Chemical Society (2003) and the Mineralogical Society of America Award (1990) should be mentioned. In 1997 he was elected as a member of the American Academy of Arts and Sciences and in 2001 as a member of the US National Academy of Sciences. He has been a member of the Phi Beta Kappa Society (since 1977), and Fellow of the Mineralogical Society of America (1990), the American Physical Society (1996) and the American Geophysical Union (1997).

He has lectured at major universities in North America, Europe and Japan, organized successful international courses and symposia, and has collaborations with international laboratories and institutes throughout the world, including Europe's first Centre for Science of Extreme Condition at Edinburgh.

Russell J. Hemley has published more than 480 papers, of which approximately 100 have been in high impact journals such as *Science, Nature*, and *Physical Review Letters*. He has edited five books, including *Ultrahigh-Pressure Mineralogy*, *Reviews in Mineralogy*, Vol. 37, Washington, D.C., Mineralogical Society of America, 1998. He has also spearheaded new methods for the synthesis of diamond and has seven patents (awarded and pending) related to diamond and superhard materials.

Ho-kwang (David) Mao, born in Shanghai, China, in 1941, is a US citizen.

Senior Staff Scientist at the Geophysical Laboratory of the Carnegie Institution of Washington, since 2005 Einstein Professor of the Chinese Academy of Sciences and Guangbiao Chair Professor of Zhejiang University.

He received his BS from the National Taiwan University, Taipei (1963), and his MS (1966) and Ph.D. (1968) from the University of Rochester. In 1968 he became Postdoctoral Fellow and later Staff Member at the Geophysical Laboratory of the Carnegie Institution of Washington (since 1972). Currently he is also Visiting Professor at the Department of Geophysical Sciences and James Franck Institute, University of Chicago; Einstein Professor of the Chinese Academy of Sciences; Director of High Pressure Collaborative Access Team (HPCAT) at Advanced Photon Source; Director of National Research Center for High Pressure at Jilin University (China); Associate Director of the Carnegie/DOE Alliance Center (CDAC) and Associate Director of the high-pressure instrument (SNAP) at Spallation Neutron Source at Oak Ridge National Laboratory.

He is the recipient of the Gregori Aminoff Prize in Crystallography (2005) from the Royal Swedish Academy of Sciences, the Roebling Medal (2005) from the Mineralogical Society of America, the Arthur L. Day Prize and Lectureship from the US National Academy of Sciences (1990), the P. W. Bridgman Gold Medal Award (1989) from the International Association for the Advancement of High Pressure Science & Technology (AIRAPT) and the Mineralogical Society of America Award (1979). He was elected as a member of the US National Academy of Sciences in 1993, a member of the Academia Sinica (Republic of China) in 1994, and Foreign Member of the Chinese Academy of Sciences (People's Republic of China) in 1996. He was elected as Fellow of the American Geophysical Union, the American Physical Society, the Geochemical Society in America, the European Association for Geochemistry and the Mineralogical Society of America.

Ho-kwang Mao has published about 660 scientific articles documenting the properties of Earth, planetary and technological materials at high compressions.

Some of the recent papers published jointly by Russell J. Hemley and Ho-kwang Mao are:

- Mao, W. L., H. K. Mao, Y. Meng, P. J. Eng, M. Y. Hu, P. Chow, Y. Q. Cai, J. Shu, and R. J. Hemley, X-ray induced dissociation of H_2O and formation of an O_2-H_2 alloy at high pressure, *Science*, 314, 636-638 (2006).
- Mao, W. L., H. K. Mao, W. Sturhahn, J. Zhao, V. B. Prakapenka, Y. Meng, J. Shu, Y. Fei, and R. J. Hemley, Iron-rich post-perovskite and the origin of ultralow-velocity zones, *Science*, 312, 564-565 (2006).
- Young, A. F., C. Sanloup, E. Gregoryanz, S. Scandolo, R. J. Hemley, and H. K. Mao, Synthesis of novel transition metal nitrides IrN_2 and OsN_2, *Phys. Rev. Lett.*, 96, 155501 (2006).
- Struzhkin, V.V., H. K. Mao, J. F. Lin, R. J. Hemley, J. S. Tse, Y. Ma, M. Hu, and C. C. Kao, Valence band x-ray emission spectra of compressed germanium, *Phys. Rev. Lett.*, 96, 137402 (2006).
- Lin, J.F., E. Gregoryanz, V. V. Struzhkin, M. Somayaulu, H.K. Mao, and R.J. Hemley, Melting behavior of H_2O at high pressures and temperatures, *Geophys. Res. Lett.*, 32, L11306 (2005).
- Lin, J.F., V. Struzhkin, S.D. Jacobsen, M.Y. Hu, P. Chow, J. Kung, H. Liu, H.K. Mao, and R. J. Hemley, Spin transition of iron in magnesiowustite in the Earth's lower mantle, *Nature*, 436, 377-380 (2005).
- Lin, J.F., W. Sturhahn, J. Zhao, G. Shen, H.K. Mao, and R.J. Hemley, Sound velocities of hot dense iron: Birch's law revisited, *Science*, 308, 1892-1894 (2005).
- Hemley, R.J., H.K. Mao, and V.V. Struzhkin, Synchrotron radiation and high pressure: new light on materials under extreme conditions, *J. Synch. Radiation*, 12, 135-154 (2005).
- Li, J., V.V. Struzhkin, H.K. Mao, J. Shu, R.J. Hemley, Y. Fei, B. Mysen, P. Dera, V. Prakapenka, and G. Shen, Electronic spin state of iron in lower mantle perovskite, *Proc. Nat. Acad. Sci.*, 101, 14027-14030 (2004).
- Santoro, M., E. Gregoryanz, H.K. Mao, and R.J. Hemley, New phase diagram of oxygen at high pressure and temperature, *Phys. Rev. Lett.*, 93, 265701 (2004).

International Balzan Foundation

The International Balzan Foundation was established in Lugano in 1956 thanks to the generosity of Angela Lina Balzan, who had come into a considerable inheritance on the death of her father, Eugenio. She destined this wealth to honour her father's memory.

Eugenio Francesco Balzan was born in Badia Polesine, near Rovigo (Northern Italy), on 20 April 1874 into a family of once wealthy landowners. He spent almost his entire working life at Milan's leading daily paper "Corriere della Sera". After joining the paper in 1897, he worked his way through successively as an editorial assistant, editor-in-chief and special correspondent. In 1903 editor Luigi Albertini made him managing director of the paper's publishing company; he then became a partner and share-holder in the company. He was not only a clever and skilful manager but also a leading personality in Milan. In 1933 he left Italy due to opposition from the Fascist regime's hostility to an independent "Corriere". He then moved to Switzerland, living between Zurich and Lugano, where for years he had invested his fortune with success. He also continued his charitable activities in favour of institutions and individuals. After returning to Italy in 1950, Eugenio Balzan died in Lugano, Switzerland, on 15 July 1953.*

The Balzan Foundation, which is international in character and scope, acts jointly through two Foundations: one under Italian law and the other under Swiss law.
The *International E. Balzan Prize Foundation - "Prize"*, with a registered office in Milan, has the aim to promote, throughout the world, culture, science, and the most meritorious initiatives in the cause of humanity, peace and brotherhood among peoples, regardless of nationality, race or creed. This aim is attained through the annual award of four prizes in two general fields: literature, the moral sciences and the arts; medicine and the physical, mathematical and natural sciences.
Nominations for the prizes in the scientific and humanistic fields are received at the Foundation's request from the world's leading learned societies. Candidates are selected by the *General Prize Committee*, composed of eminent European scholars and scientists. Since 2001, each prize is worth one million Swiss francs, half of which the prizewinner must destine for research work or studies for the promotion of science and culture, preferably involving young researchers.
At intervals of not less than three years, the Balzan Foundation also awards a "Prize for humanity, peace and brotherhood among peoples", of varying amounts.
The *International E. Balzan Prize Foundation - "Fund"*, with a registered office in Zurich, shares these aims and administers Eugenio Balzan's estate.

* Renata Broggini, *Eugenio Balzan 1874-1953. Una vita per il "Corriere", un progetto per l'umanità*, Milano, 2001.

List of Balzan Prizewinners

Sciences and Humanities

2006	**Ludwig Finscher** (Germany)	*History of Western Music since 1600*
	Quentin Skinner (UK)	*Political Thought; History and Theory*
	Paolo de Bernardis (Italy) and **Andrew Lange** (USA)	*Observational Astronomy and Astrophysics*
	Elliot Meyerowitz (USA) and **Christopher Somerville** (USA/Canada)	*Plant Molecular Genetics*
2005	**Peter Hall** (UK)	*The Social and Cultural History of Cities since the Beginning of the 16th Century*
	Lothar Ledderose (Germany)	*The History of the Art of Asia*
	Peter e **Rosemary Grant** (USA/UK)	*Population Biology*
	Russell Hemley (USA) and **Ho-kwang Mao** (USA/China)	*Mineral Physics*
2004	**Pierre Deligne** (USA/Belgium)	*Mathematics*
	Nikki Ragozin Keddie (USA)	*The Islamic world from the end of the 19th to the end of the 20th century*
	Michael Marmot (UK)	*Epidemiology*
	Colin Renfrew (UK)	*Prehistoric Archaeology*
2003	**Reinhard Genzel** (Germany)	*Infrared Astronomy*
	Eric Hobsbawm (UK/Egypt)	*European History since 1900*
	Wen-Hsiung Li (USA/Taiwan)	*Genetics and Evolution*
	Serge Moscovici (France/Romania)	*Social Psychology*

2002	**Walter Jakob Gehring** (Switzerland)	*Developmental Biology*
	Anthony Thomas Grafton (USA)	*History of the Humanities*
	Xavier Le Pichon (France)	*Geology*
	Dominique Schnapper (France)	*Sociology*
2001	**James Sloss Ackerman** (USA)	*History of Architecture*
	Jean-Pierre Changeux (France)	*Cognitive Neurosciences*
	Marc Fumaroli (France)	*Literary History and Criticism (post 1500)*
	Claude Lorius (France)	*Climatology*
2000	**Ilkka Hanski** (Finland)	*Ecological Sciences*
	Michel Mayor (Switzerland)	*Instrumentation and Techniques in Astronomy and Astrophysics*
	Michael Stolleis (Germany)	*Legal History since 1500*
	Martin Litchfield West (UK)	*Classical Antiquity*
1999	**Luigi Luca Cavalli-Sforza** (USA/Italy)	*Science of Human Origins*
	John Elliott (UK)	*History, 1500-1800*
	Mikhael Gromov (France/USSR)	*Mathematics*
	Paul Ricœur (France)	*Philosophy*
1998	**Harmon Craig** (USA)	*Geochemistry*
	Robert McCredie May (UK/Australia)	*Biodiversity*
	Andrzej Walicki (USA/Poland)	*The cultural and social history of the Slavonic world from the reign of Catherine the Great to the Russian revolutions of 1917*
1997	**Charles Coulston Gillispie** (USA)	*History and Philosophy of Science*
	Thomas Wilson Meade (UK)	*Epidemiology*
	Stanley Jeyaraja Tambiah (USA/Ceylon)	*Social Sciences: Social Anthropology*

1996	**Arno Borst** (Germany)	*History: Medieval Cultures*
	Arnt Eliassen (Norway)	*Meteorology*
	Stanley Hoffmann (USA/France/Austria)	*Political Sciences: Contemporary International Relations*
1995	**Yves Bonnefoy** (France)	*Art History and Art Criticism (as applied to European Art from the Middle Ages to our times)*
	Carlo M. Cipolla (Italy)	*Economic History*
	Alan J. Heeger (USA)	*Science of New Non-Biological Materials*
1994	**Fred Hoyle** (UK) and **Martin Schwarzschild** (USA/Germany)	*Astrophysics (evolution of stars)*
	René Couteaux (France)	*Biology (cell-structure with special reference to the nervous system)*
	Norberto Bobbio (Italy)	*Law and Political Science (governments and democracy)*
1993	**Wolfgang H. Berger** (USA/Germany)	*Paleontology with special reference to Oceanography*
	Lothar Gall (Germany)	*History of the 19th and 20th centuries*
	Jean Leclant (France)	*Art and Archeology of the Ancient World*
1992	**Armand Borel** (USA/Switzerland)	*Mathematics*
	Giovanni Macchia (Italy)	*History and Criticism of Literatures*
	Ebrahim M. Samba (Gambia)	*Preventive Medicine*
1991	**John Maynard Smith** (UK)	*Genetics and Evolution*
	György Ligeti (Austria/Hungary)	*Music*
	Vitorino Magalhães Godinho (Portugal)	*History: The emergence of Europe in the 15th and 16th centuries*

1990	**Pierre Lalive d'Epinay** (Switzerland)	*Private International Law*
	James Freeman Gilbert (USA)	*Geophysics (solid earth)*
	Walter Burkert (Germany)	*Study of the Ancient World (Mediterranean area)*
1989	**Martin John Rees** (UK)	*High Energy Astrophysics*
	Leo Pardi (Italy)	*Ethology*
	Emmanuel Lévinas (France/Lithuania)	*Philosophy*
1988	**Michael Evenari** (Israel) and **Otto Ludwig Lange** (Germany)	*Applied Botany (including ecological aspects)*
	René Etiemble (France)	*Comparative Literature*
	Shmuel Noah Eisenstadt (Israel)	*Sociology*
1987	**Phillip V. Tobias** (South Africa)	*Physical Anthropology*
	Jerome Seymour Bruner (USA)	*Human Psychology*
	Richard W. Southern (UK)	*Medieval History*
1986	**Jean Rivero** (France)	*Basic Human Rights*
	Otto Neugebauer (USA/Austria)	*History of Science*
	Roger Revelle (USA)	*Oceanography/Climatology*
1985	**Ernst H.J. Gombrich** (UK/Austria)	*History of Western Art*
	Jean-Pierre Serre (France)	*Mathematics*
1984	**Jan Hendrik Oort** (Netherlands)	*Astrophysics*
	Sewall Wright (USA)	*Genetics*
	Jean Starobinski (Switzerland)	*History and Criticism of Literatures*

1983	**Francesco Gabrieli** (Italy)	*Oriental Studies*
	Ernst Mayr (USA/Germany)	*Zoology*
	Edward Shils (USA)	*Sociology*
1982	**Jean-Baptiste Duroselle** (France)	*Social Sciences*
	Massimo Pallottino (Italy)	*Sciences of Antiquity*
	Kenneth Vivian Thimann (USA/UK)	*Pure and Applied Botany*
1981	**Josef Pieper** (Germany)	*Philosophy*
	Paul Reuter (France)	*International Public Law*
	Dan Peter McKenzie, Drummond Hoyle Matthews and **Frederick John Vine** (UK)	*Geology and Geophysics*
1980	**Enrico Bombieri** (Italy)	*Mathematics*
	Jorge Luis Borges (Argentina)	*Philology, Linguistics and Literary Criticism*
	Hassan Fathy (Egypt)	*Architecture and Town-planning*
1979	**Jean Piaget** (Switzerland)	*Social and Political Sciences*
	Ernest Labrousse (France) and **Giuseppe Tucci** (Italy), *ex aequo*	*History*
	Torbjörn Caspersson (Sweden)	*Biology*
1962	**Karl von Frisch** (Austria)	*Biology*
	Andrej Kolmogorov (USSR)	*Mathematics*
	Paul Hindemith (Germany)	*Music*
	Samuel Eliot Morison (USA)	*History*

Humanity, Peace and Brotherhood among Peoples

2004 Community of Sant'Egidio - DREAM programme

2000 Abdul Sattar Edhi (Pakistan)

1996 International Committee of the Red Cross

1991 Abbé Pierre (France)

1986 United Nations Refugee Agency (UNHCR)

1978 Mother Teresa of Calcutta (Jugoslavia)

1962 H.H. John XXIII (Italy)

1961 Nobel Foundation

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