Department of Earth, Atmospheric and Planetary Sciences

The Department of Earth, Atmospheric and Planetary Sciences (EAPS) studies Earth, planets, climate, and life and has broad intellectual horizons encompassing the solid Earth, its fluid envelopes, and its neighbors throughout the solar system and beyond. The department seeks to understand fundamental physical, chemical, and biological processes that define the origin, evolution, and current state of these systems, and to use this understanding to predict future states. The department comprises 40 faculty members, including three with a primary appointment in the Department of Civil and Environmental Engineering, one with a primary appointment in the Institute for Data, Systems, and Society, and another with a primary appointment in the Department of Aeronautics and Astronautics. There are also more than 310 research staff, postdoctoral associates, and visiting scholars.

EAPS is noted for its emphasis on interdisciplinary problems and is involved in numerous laboratories, centers, and programs that address broad questions in the Earth sciences, including those that are among the most pressing societal issues of our time: changes in climate and environment, natural resources and hazards, and the origin and evolution of life on Earth and, perhaps, elsewhere. For example, the Earth Resources Laboratory (under the directorship of Professor Bradford Hager) integrates faculty, staff, and students across disciplinary, departmental, and school boundaries to investigate geophysical and geological problems in energy and resource development. The Center for Global Change Science (under the directorship of Professor Ronald Prinn) builds cross-Institute activity in meteorology, oceanography, hydrology, chemistry, satellite remote sensing, and policy. The Lorenz Center (under the co-directorship of Professors Kerry Emanuel and Daniel Rothman) aspires to be a climate think tank devoted to fundamental scientific inquiry. Furthermore, EAPS is MIT's largest participant in the MIT/Woods Hole Oceanographic Institution (MIT/WHOI) Joint Program for graduate education and research in ocean sciences and engineering.

Educational Activities

The EAPS faculty is committed to the development and maintenance of vibrant education programs at both the undergraduate and graduate level. Student engagement with the education program is a continuing departmental goal. Graduate students meet with the department head and associate head at least once per term to discuss concerns and issues arising in their respective programs with the goal of sustaining active and open conversations around educational issues.

Graduate Program

EAPS has vigorous graduate educational programs in the areas of Earth, planets, climate, and life, including geology, geochemistry, geobiology, geophysics, atmospheres, oceans, climate, and planetary science. The Committee on Graduate Programs approved the joint EAPS/Woods Hole Oceanographic Institution proposal to add biological oceanography as a thesis field in the department. This addition will provide an appropriate departmental home for graduate students who have a strong oceanographic focus in their ocean biology, physiology, and ecology research. In fall 2016, EAPS had

149 graduate students registered in the department, including 74 students in the MIT/WHOI Joint Program and one fifth-year master's degree student. Women constituted 45% of the graduate student population, and 6% of graduate students were members of an underrepresented minority group.

The excellence of the EAPS graduate program is built not only on the strength of teaching and supervision by the faculty but also on the involvement of EAPS graduate students in departmental activities. Students develop formal and informal ways of improving their educational experience and student life. For example, the graduate students continue to take responsibility for an expanded orientation program for incoming graduate students. They plan a number of social events to introduce the newcomers to EAPS, MIT, and the Cambridge area. The department graduate students meet regularly, with one student presenting his or her research to the student body at the weekly Graduate Student Seminar. Undergraduate majors are encouraged to attend these talks. The departmental Graduate Student Mentoring Program continues to be a well-received approach to providing peer support for new students.

The department awards an annual prize for excellence in teaching to highlight the superior work of its teaching assistants. During the 2017 academic year, Alissa Earle, Lauren Kipp, Rohini Shivamoggi, Eric Stansifer, and Martin Wolf were recognized for their contributions.

EAPS students were garnered recognition from MIT, from professional societies, and from outside organizations. Michael McClellan was awarded MIT's 2017 Karl Taylor Compton Prize. The Karl Taylor Compton Prize is the highest award presented by the Institute to a student or student organization "in recognition of excellent achievements in citizenship and devotion to the welfare of MIT." Marjorie Cantine and Kelsey Moore were selected as 2017 MIT Graduate Women of Excellence. Lauren Kipp was awarded the School of Science Graduate Teaching Award. Hannah Mark received an Outstanding Student Paper Award at the fall 2016 meeting of the American Geophysical Union for her work, "Seismic Coupling at Divergent Plate Boundaries from Rate-and-State Friction Models." This work was also recognized with an honorable mention for the GeoPRISMS Student Prize. Adam Sarafian won the Castaing Award for best student presentation at the 2016 Microscopy and Microanalysis Conference.

The Department of Earth, Atmospheric and Planetary Sciences graduated 30 doctoral students and five master's degree students in AY2017.

Undergraduate Program

EAPS had 19 undergraduate majors in AY2017, 75% percent of whom were women, and 5% of whom were members of an underrepresented minority group. The EAPS undergraduate population has always been small, but satisfaction is high, and the department continues its efforts to increase the number of students majoring in the department. To further this goal, EAPS has reorganized the degree requirements for the major. Although the subjects remain essentially the same, they have been organized into four concentration areas (geoscience; atmospheres, oceans, and climate; planetary science and astronomy; and environmental systems) to make a student's subject selection easier. Other activities include events for incoming freshmen, involvement through freshman advising and teaching beyond EAPS, widened use of social media, and increased visibility on campus.

The department maintains a strong presence in undergraduate education across MIT so that the general MIT student body has ready access to education in geo-scientific aspects of climate and environmental change, natural hazards, and natural energy resources. Michael Follows co-taught an ecology class with the Department of Civil and Environmental Engineering. EAPS faculty members with joint appointments (Kerri Cahoy, Noelle Selin, Collette Heald, Ruben Juanes, Dara Entekhabi) are also active in teaching undergraduates. The department supports and provides leadership for two major undergraduate programs at MIT, Terrascope (under the directorship of Professor David McGee) and the Experimental Studies Group (under the directorship of Professor Leigh Royden). EAPS also offers a relatively large number of freshman advising seminars. With the combined enrollment of Terrascope and the advising seminars, as well as the Experimental Studies Group, EAPS connected with seven percent of the students in the freshman class on a weekly basis. Similarly, EAPS continues to be an active participant in three interdisciplinary minor programs: the broadly based energy minor, the astronomy minor (with the Department of Physics) and the atmospheric chemistry minor (with the Departments of Chemistry, AeroAstro, Civil and Environmental Engineering, and the Institute for Data, Systems, and Society). EAPS looks forward to participation in the newly approved environment and sustainability minor.

At the 2017 Student Awards and Recognition Dinner, the Goetze Prize was awarded to Costa D. Christopoulos (advised by Professor Dan Cziczo) in recognition of his outstanding senior thesis. Brynna G. Downey received the W. O. Crosby Award for Sustained Excellence, recognizing her achievement, both academic and intellectual, as well as her general contributions to the department. Lilian A. Dove was the recipient of the EAPS Achievement Award, which recognizes a rising senior from across the EAPS disciplines. The award is presented to a student who has distinguished themselves through a combination of high grade point average, focused course work, and leadership. Kaylee Brent was recognized as an outstanding undergraduate teaching assistant for her work in 12.000 Solving Complex Problems, and Taylor Safrit was recognized for his work with the students in 12.409 Hands on Astronomy: Observing Stars and Planets. Nicholas Hoffman was selected as a 2017 Burchard Scholar by the School of Humanities, Arts, and Social Sciences. Madonna Yoder received the Award for Excellence in Undergraduate Research from the Sea Grant program for her research on the Lower Charles River Chart project.

EAPS graduated seven bachelor’s degree students in AY2017.

Faculty

The department continues in its efforts to hire the best young scientists and help them develop successful careers.

Matěj Pěc, a geologist, who recently completed a postdoctoral appointment at the University of Minnesota, joined the department in January 2017.

EAPS also welcomed Andrew Babbin in January 2017. Babbin is a marine biogeochemist who recently completed a postdoctoral appointment at MIT in the Department of Civil and Environmental Engineering.

EAPS is now halfway through the sixth year of the junior faculty mentorship program introduced in January 2012. Each junior faculty member is assigned a mentor team comprising a primary mentor (often a close colleague) and two senior faculty members from outside the candidate's disciplinary group. They meet as a group once a semester and report to the department head. Junior and senior faculty members alike are satisfied with the new system. Feedback solicited from junior faculty will be used to make further improvements.

Promotions

Associate Professor of Oceanography Michael Follows was promoted to the rank of full professor with tenure (effective July 2017).

Assistant Professor of Environmental Science David McGee was promoted to the rank of associate professor without tenure (effective July 2017).

Communications

The EAPS Communications Office continues to produce the department's monthly e-newsletter, EAPSpeaks (sent to more than 2,600 people), and its annual print magazine, *EAPS Scope*. Both publications rely on the rich stream of news stories available on the EAPS web page (approximately 230 stories for the 12 months beginning July 1, 2016). Over the same time, the number of EAPS followers on Facebook continued to grow steadily from a little less than 6,000 to more than 7,100.

The EAPS Program in Atmospheres, Oceans, and Climate (PAOC), one of the four academic research programs in EAPS, maintains its own independent website. Faculty in PAOC employ a writer (Lauren Hinkel) to prepare stories about activities in that program. Beginning in late spring 2017, it was agreed that she would coordinate more closely with the EAPS communications team. Lauren Hinkel joins Jennifer Fentress, who is responsible for the design, brand management, marketing, and preparation of *EAPS Scope*; Heather Queyrouze Wagner, who is responsible for day-to-day management of the EAPS website, social media, and preparation of EAPSpeaks; and Communications Officer Helen Hill, who continues to provide science writing, create multimedia content, and supply strategic and technical oversight.

Major initiatives in AY2017 have included design and implementation from the ground up of an undergraduate recruitment campaign with the goal of increasing the number of Course 12 undergraduates. The "Go Beyond" campaign pairs strong, short taglines with compelling imagery across printed materials from brochures to posters and on a stand-alone website. Department leadership is looking forward to working with the new EAPS education officer to develop this campaign further.

Inadvertently, the department's news channels (the website and social media) have become dominated by stories related to climate and planetary science; there have been notably fewer stories spotlighting activity in other geoscience areas. A particular goal for AY2018 is to instigate a rise in the number of news stories featuring geoscience.

Development

During fiscal year 2017, the EAPS senior development officer focused development efforts on the capital campaign, on planned gifts, on fundraising for research needs, and on building discretionary funds and fellowships. New gifts and pledges to EAPS in FY2017 totaled $10.7 million—a fourfold increase from FY2016. The increase was largely due to an influx of capital gifts, planned gifts, and major gifts and foundation grants for research.

In FY2017, MIT approved the plan to meet EAPS's pressing space needs by designating "wet" laboratory space to be renovated in Building 4, and also by building an addition to the Green Building for program space. This approval is subject to the department's raising a total of $30 million in capital gifts. EAPS Visiting Committee members Neil Pappalardo and Neil Rasmussen, along with MIT Corporation Chair Emeritus John Reed, are acting as a de facto think tank for the department's building plans and fundraising efforts. Thanks to gifts from Neil Rasmussen and Neil Pappalardo, a total of $4 million was committed for capital funding needs in FY2017. With several other solicitations under way, the department looks forward to gaining momentum with its capital fundraising through FY2018 and beyond.

Major gifts totaling $560,000 were also received from individual donors for the Search for Habitable Planets Eclipsing Ultra-Cool Stars exoplanet research project, climate research, the Women in XII Fund, and the Callahan-Dee Fellowship Fund. Foundation support for research was $1.82 million. Several of these foundation grants were facilitated through a collaboration between faculty, the EAPS senior development officer, and colleagues in MIT's Office of Foundation Relations.

In addition, $2.96 million was received in new planned gifts during FY2017 (mostly charitable remainder unitrusts). This long-term investment provides assurance that EAPS will be able to attract students and faculty of the highest caliber for decades to come. Most planned gifts involved close collaboration between the EAPS senior development officer and colleagues in the Office of Gift Planning and the Office of the Recording Secretary.

Graduate student support remains an important development priority for EAPS. In FY2017 the department received $430,000 toward expendable graduate fellowships, the majority through the generosity of EAPS Visiting Committee members. Annual and newsletter appeals resulted in an additional $200,000 to build named endowed fellowship funds (the Elliot, Madden, Toksöz, and Treitel funds) and the EAPS Discretionary and Graduate Student Support Funds.

Among many visits, events, and reports to donors throughout the year, a number of stewardship and outreach events deserve particular mention, as these illustrate the considerable effort and teamwork contributed by faculty members, students, and colleagues in EAPS headquarters (notably Allison Provaire, Brandon Milardo, Helen Hill, Jen Fentress, and Heather Queyrouze Wagner).

EAPS hosted a celebration of the Pauline Austin Centenary in December 2016. The late Pauline Austin's family members joined former peers and students to remember her work as director of MIT's Weather Radar Research Project and to unveil a display on the 16th floor of the Green Building that celebrates her life. The display and celebration were made possible by an anonymous donor, whose gift also facilitated the acquisition of new equipment for the synoptic teaching laboratory.

The third annual EAPS Patrons Circle appreciation dinner for major donors to EAPS fellowship funds was held in April 2017. The EAPS Patrons Circle now has 32 members. Patrons who attended enjoyed a poster session from students and scientific presentations from Maria Zawadowicz (2017 Grayce B. Kerr Fellow) and EAPS postdoctoral associate Julien de Wit (2012 Grayce B. Kerr Fellow). The celebratory event concluded with remarks from EAPS Patrons Circle Chair Neil E. Rasmussen ’76, SM ’80.

In September 2016, EAPS Head of Department Robert van der Hilst and Richard P. Binzel hosted a group of alumni and friends on a visit to Cape Canaveral, FL, to witness the Osiris-Rex launch. Maria Zuber, vice president of research, joined us to speak at a welcome dinner on the eve of the successful launch.

In October 2016, EAPS and the Lorenz Center hosted the sixth annual John H. Carlson Climate Science Lecture, “Big Ice, Antarctica, Greenland, and Boston,” by Richard Alley, at the New England Aquarium, attracting more than 200 guests. Seventy-five guests, faculty members, and students attended a private dinner following the lecture.

EAPS hosted the public William F. Brace Lecture, and, with the Center for Global Change Science, co-hosted the Henry P. Kendall Lecture at MIT. EAPS and the Earth Resources Laboratory co-hosted an annual reception for EAPS alumni and friends during the Society of Exploration Geophysicists meeting in Dallas, TX, in October 2016. EAPS also hosted a reception during the American Geophysical Union (AGU) annual meeting in San Francisco, CA, in December 2016.

During the past year, EAPS Senior Development Officer Angela Ellis partnered with faculty and various colleagues in the School of Science, Resource Development, and the MIT Alumni Association (MITAA) to highlight EAPS research through internal presentations to fundraisers as well as regional and local alumni events: Benjamin Weiss spoke about his research to the MIT Club in Cleveland, Ohio; Sara Seager spoke at events in Santa Barbara and San Francisco, CA; and Amanda Bosh spoke at Tech Reunions at MIT. Richard Binzel and Paola Rizzoli have starred in online events hosted by MITAA. Many EAPS faculty are also recruited to lead trips with the MITAA Travel Program and we continue to partner on outreach and follow-up efforts.

During FY2018, fundraising will be increasingly concentrated on the EAPS capital campaign that is now an integral part of MIT’s Campaign for a Better World. The department hopes to secure an additional 20,000 square feet of space that will include modernized laboratory and teaching facilities in Building 4. The new space should include an exciting addition to the Green Building that will provide an attractive focal point on campus for “earth and environment” while enabling EAPS to recruit and retain the best faculty and students for years to come.

We look forward to continuing our close partnership with colleagues from the School of Science, the Office of Resource Development, and MITAA on outreach and major gifts, and are optimistic that MIT alumni and friends will continue to magnify the impacts of EAPS research into the Earth, planets, climate, and origins of life through their generous philanthropic support.

Faculty Research Highlights

Andrew Babbin

Assistant Professor Babbin is a seagoing biogeochemist studying how ocean chemistry regulates marine microbial metabolisms, particularly with respect to nitrogen cycling. His new group operates at the interface of chemical oceanography and marine microbiology, investigating the interactions among the rates of diverse metabolic reactions, the distribution of microbial clades, and the underlying chemistry across marine ecosystems. Two recent research cruises have been completed, one studying seawater chemistry across the Pacific basin, and another specifically targeting the biogeochemistry of the hydrothermal vent systems along the East Pacific Rise. Construction of the Babbin laboratory has just been completed in Building 54, permitting new experiments to probe how individual bacterial strains respond to specific physicochemical stressors to affect microbial function, community composition, and the resultant marine biogeochemistry.

Kristin Bergmann

Assistant Professor Bergmann's research group studies the ancient interactions between the environment and early complex life. In particular, her group studies the nature of carbonate sedimentation through time and reconstructs temperature records from rocks from approximately 1 billion to 443.8 million years ago. The Bergmann Lab uses a combination of approaches including fieldwork, micro-analytical methods (including electron microprobe techniques and secondary ion mass spectrometry), and carbonate clumped isotope geochemistry.

During the fall of 2017, the Bergmann group installed a Nu Perspective Isotope Ratio Mass Spectrometer into the newly renovated lab space on the 10th floor of Building 54. Three field seasons were conducted during the past year, one to Svalbard, Norway, to sample strata from the Neoproterozoic to the Ordovician (541 million to 443.8 million years ago), one to the area outside Death Valley National Park in California and Nevada, and one to Anticosti Island in Canada. Bergmann also taught a new Independent Activities Period course, Earth's Sandbox: Mass Extinctions, and a second year of Sedimentary Environments and Sedimentology in the Field, which took nine students to the Death Valley area over spring break to study rocks that are 530 million years old. Bergmann collaborated with MIT Libraries and the Geographic Information Systems laboratory to introduce drone technology to the fieldwork and classwork.

Edward Boyle

Professor Edward Boyle's group completed an oceanographic section for lead and lead isotopes from sections in the Arctic Ocean (Bering Sea to the North Pole). There is no previously published data on lead in the Arctic Ocean. Lead concentrations in the Bering Sea are high, with a distinctive isotopic composition from Asian sources, but most of this Pacific lead is lost through continental shelf biogeochemical processes during transit through the shallow Bering Strait. The most recent Atlantic waters entering just below the shallower Pacific waters show higher lead and lead isotope ratios and different isotope ratios. Because the residence time of waters at the North Pole and Canada Basin is very long (measured in centuries), lead concentrations are very low because of limited anthropogenic connection during the recent century.

The Boyle group also developed a new method for the determination of chromium isotopes in seawater and applied this redox-sensitive tracer to oceanographic profiles from the Arctic, the Central North Pacific, the Mexican oxygen-deficient zone , and the anoxic bottom waters of the Santa Barbara Basin. Chromium isotope ratios are being used by geologists to assess oxygen conditions in the distant geological past, but there is very little data from the modern environment to allow the assessment and modeling of chromium isotope behavior. Chromium isotope analysis of trace-level chromium in seawater is very difficult and has been achieved by only two or three groups in the world. The Arctic data is very similar to published chromium isotope data from this basin, and the open ocean data fall in a consistent chromium isotope–log[chromium] relationship consistent with Rayleigh fractionation due to redox transformations. Heavy chromium isotopes are enriched in the anoxic waters of the Mexican oxygen deficient zone and in the bottom waters of the Santa Barbara Basin because of the reduction of chromium from chromium(VI) to the lighter chromium(III) and removal of the lighter chromium(III) by scavenging onto sinking particles.

Timothy Cronin

Assistant Professor of Atmospheric Science Timothy Cronin started his appointment on July 1, 2016; his first year at EAPS was focused on growing his group and developing his research program on climate, clouds, and atmospheric convection. Cronin began co-advising third-year PhD student Tom Beucler together with Professor Kerry Emanuel. Beucler and Cronin co-authored a paper on how the tropical atmosphere may be unstable, separating into moist and dry regions due to interactions between atmospheric water vapor content and radiative heating rates.

Tristan Abbott began in September 2016 as a first-year PhD student advised by Cronin. James S. MacDonnell Foundation Postdoctoral Fellow Daniel Koll joined the group in February 2017. Cronin taught 12.815: Atmospheric Radiation and Convection in fall 2016. Cronin continued a collaboration with Harvard University Professor Eli Tziperman, and together with a former summer student they published a paper on how the formation of very cold air masses is likely to be suppressed in a warmer world by increasing insulation from thick clouds. Cronin was awarded a National Science Foundation (NSF) grant as co–principal investigator on a study directed at understanding the temperature-dependence of climate feedbacks. Cronin also served as a science advisor for the WGBH–NASA project, Bringing the Universe to America's Classrooms.

Daniel Cziczo

The focus of Daniel Cziczo's research group is on understanding the chemical composition, size, and morphology of small atmospheric particles, commonly termed aerosols, and how these various properties affect the uptake of water. The group is organized around answering four questions:

- *How do particles in the Earth's atmosphere, in particular those produced by human activities, affect the planet's climate?* Researchers in the Cziczo laboratory seek to answer this question because the largest uncertainty in understanding the Earth's climate is the formation and persistence of clouds. The uncertainty is caused by several poorly understood processes and measurements, including the microphysics of how particles nucleate droplets and ice, the number of droplet- and ice-forming particles as a function of such atmospheric properties as temperature and relative humidity, the atmospheric distribution of droplet- and ice-forming particles, and the role of anthropogenic activities in producing or changing the behavior of droplet- and ice-forming particles. The major focus of the group is organized around a set of projects aimed at reducing uncertainty in these areas. Researchers in the Cziczo laboratory use a combination of laboratory, fieldwork, and modeling studies to accomplish this goal. Secondary research foci in the field of atmospheric chemistry include understanding the role of aerosols in visibility, heterogeneous chemistry, and the initiation of precipitation (i.e., the role of aerosols in the Earth's water cycle).

- *Do we have the right instruments to answer the questions we are interested in?* Laboratory members are actively involved in the development of new instruments for laboratory and field use. A major group goal has been miniaturization of instruments so that researchers can access remote field sites with limited space and power, as well as deploy instruments on unmanned aerial vehicles. Development activities include ongoing partnerships with private industry (e.g., with Aerodyne, Inc., and Droplet Measurement Technologies) as well as government laboratories (e.g., the National Oceanic and Atmospheric Administration's Chemical Sciences Division).

- *Do clouds around other planets, both within and beyond our solar system, limit our understanding of those planets?* The Cziczo group's expertise and instrumentation for terrestrial aerosols and cloud formation can be leveraged to address topics of interest in other fields. In planetary sciences, Cziczo laboratory members have extended the capabilities of cloud chambers designed and built for terrestrial studies to examine conditions found on other planets. Studies include determination of conditions required for cloud formation in the Martian atmosphere and mimicking exoplanet cloud formation.

- *Can current instrumentation for atmospheric studies be used to understand pre-industrial aerosols?* In the field of paleoclimatology, researchers have sought to address another of the large uncertainties in understanding climate change: the lack of data characterizing the pre-industrial aerosol loading of the atmosphere. Modern instrumental records of aerosols date back, at most, a few decades. To overcome this limitation, the Cziczo group has used a single particle mass spectrometer to characterize aerosol trapped within ice cores. With this method, researchers can use a modern technique to characterize aerosols dating back hundreds, possibly thousands, of years. The goal is to "stitch" pre-industrial records to contemporary records with a common instrumental technique.

Daniel J. Cziczo, associate professor of both EAPS and the Department of Civil and Environmental Engineering, was elected in 2016 to the chair of the President's Advisory Committee on University Relations, on which he has served since 2013. He has also served as MIT's member representative to the University Corporation for Atmospheric Research since 2014 and participated in that consortium's meetings with members of Congress in 2017. Cziczo is a co-editor of *Atmospheric Chemistry and Physics*. He advised a number of students, including postdoctoral fellows A. V. Johnson, M. Roesch, and C.

Roesch; doctoral students Maria Zawadowicz, Martin Wolf (who received the EAPS outstanding teaching assistant award) and Tyler Erjavec; and three students from the Undergraduate Research Opportunities Program, C. Christopolous, who received the EAPS outstanding thesis award, L. Koolik, and L. Dove, who received the EAPS outstanding undergraduate award. He collaborated with Visiting Scientist Kong Xiangrui of the University of Stockholm.

Cziczo contributed to three chapters of the American Meteorological Society's monograph, *Ice Formation and Evolution in Clouds and Precipitation: Measurement and Modeling Challenges*. He attended the INUIT (invited plenary), American Association for Aerosol Research (2016), and Committee on Nucleation and Atmospheric Aerosols (2017) conferences. He taught subjects 12.338/.814/1.842 Aerosol and Cloud Chemistry and Microphysics, 12.335/.835 Experimental Atmospheric Chemistry, 12.422 Planetary Atmospheres, and 12.993 The Science of Geoengineering. He also taught a course, "Climate Change: From Science to Solutions," for MIT's Professional Education Summer Short Program in summer 2016.

Kerry Emanuel

During academic year 2017, Professor Kerry Emanuel and his research group continued several lines of research and initiated several others. Graduate student Vince Agard and Professor Emanuel continued studying how severe local storms, which produce damaging wind, hail, and tornadoes, respond to climate change. They made a breakthrough in this research by showing that the energy available to severe convective storms rises exponentially with surface temperature. Diamilet Perez-Betancourt and Emanuel are exploring the dynamics of spiral rainbands in hurricanes. Graduate student Rohini Shivamoggi and Emanuel continue to study the physics of secondary eyewalls in tropical cyclones. Fuqing Zhang of Penn State and Emanuel explored the fundamental predictability of tropical cyclone intensity and published two papers on the topic. Emanuel showed that the incidence of tropical cyclones that intensify rapidly just before landfall—which present a serious forecasting problem—will probably increase as the planet continues to warm. He also participated in a project that demonstrated that Atlantic hurricanes were likely more active in the early Holocene as a consequence of the greening of the Sahara Desert. Professor Emanuel was elected to the American Academy of Arts and Sciences.

Raffaele Ferrari

Professor Raffaele Ferrari and his group continued their study of ocean circulation and its impact on climate. They are following three primary lines of research:

- Last year, the group showed that the waters that sink in the ocean abyss at high latitudes return to the surface along the slopes of abyssal seamounts and ridges, in contrast to the textbook view that these waters come back to the surface uniformly in the open ocean. This year, the Ferrari group showed that the upslope flow affects the overall abyssal ocean circulation and the residence time of heat and carbon in the abyssal ocean, with obvious climate implications. These results are attracting much attention and were recognized in Ferrari's nomination for the 2016 Scripps Cody Award.

- The periodic drop in atmospheric carbon dioxide was the key to Earth's climate having plummeted into ice ages over the past two million years. Although the oceans are believed to have taken up the atmospheric carbon dioxide during the glacial periods, the specific mechanism is not well understood. The Ferrari group showed that the expansion of sea ice around Antarctica at the inception of an ice age (driven by changes in isolation) results in additional uptake of carbon dioxide by the oceans, which further cools the atmospheric temperature, resulting in more sea ice growth, more ocean carbon dioxide uptake, and, eventually, a full ice age.
- Half of the oceans' carbon uptake is the result of photosynthesis by phytoplankton. There is an ongoing debate on whether the bulk of ocean photosynthesis starts at high latitudes in winter or spring. Using newly developed profiling floats equipped with bio-optical sensors, the group has shown that, although some photosynthesis starts in winter, the bulk of biomass production and carbon uptake does not start until spring. This result has important implications for the response of ocean photosynthesis to climate change, which the Ferrari group is now exploring.

In July 2016, the Scripps Institution on Oceanography presented Professor Ferrari the Cody Award for outstanding scientific achievement in oceanography. Student Henri Drake was awarded an National Science Foundation fellowship and Madeleine Youngs received a National Defense Science and Engineering Graduate Fellowship. The California Institute of Technology hired postdoctoral associate Joern Callies as an assistant professor. Postdoctoral associate Alizera Mashayek was awarded a United Kingdom National Environment Research Council Fellowship.

Gregory Fournier

Research progressed within the laboratory this year on several fronts.

Dating the Tree of Life. Using computational techniques and genome sequence data, this project attempts to combine genomic, paleontological, physiological, and geological and geochemical evidence with molecular clock models to calibrate the evolutionary histories of major groups of microbes, in order to estimate when they likely evolved and how their metabolisms influenced the planetary system. So far, this project has resulted in the completion of several pilot studies focusing on specific groups of microbes with biogeochemical relevance—cyanobacteria, methanogens, and lineages of photosynthetic bacteria that do not produce oxygen. Graduate student projects within the lab are currently extending this work to dating specific metabolic processes in microbial evolution, including carbon fixation and methanogenesis from acetate, amines, and sulfur compounds.

Ancestral reconstruction of the earliest proteins. Several ancient protein families diversified before the last common ancestor of all life on Earth. These protein families have essential functions in all life, and diversified through gene duplications in some of the earliest evolutionary events that comparative genomics can detect. One of these groups of proteins are the aminoacyl-tRNA synthetase proteins, which add the correct amino acid to its corresponding tRNA during protein translation. However, since these proteins have undergone substantial evolutionary changes, reconstructing their history has been very difficult and uncertain. To resolve this history better and push back the earliest record of comparative genomic information, members of the Fournier

Lab have performed intensive manual and automated structure-based alignments of these protein families, which have resulted in much higher quality phylogenetic trees that can be used to make more accurate evolutionary inferences. Reconstruction of the ancestral sequences across this tree reveals that the very earliest synthetase ancestors already had a full complement of all 20 amino acids in their sequences. This is direct evidence of an older, more primitive system for aminoacylating tRNA that predates diversification of these protein families; this may be evidence that the genetic code itself fully evolved within an earlier "RNA world," with proteins evolving later to take over these specific functions. Currently, lab members are working to improve the quality of these reconstructions with collaborators at the Tokyo Institute of Technology.

Genomes and the Rise of Oxygen. This project is a collaboration between the NASA Astrobiology Institute's MIT team on the foundations of complex life and the alternative earths team at the University of California at Riverside. Together with Roger Summons, junior researcher Abigail Caron, and postdoctoral associate David Gold, researchers are investigating the history of the emergence and spread of oxygen-related genes across microbial lineages. Mapping the evolutionary histories of these genes using phylogenies based on genome sequence data revealed how and when major groups of microbes likely first encountered oxygen and then adapted to changing levels of oxygen across more than two billion years of planetary change. This year, project scientists published a key finding: oxygen-dependent sterol biosynthesis genes shared between eukaryotes and bacteria likely originated by 2.3 billion years ago, about the same time as oxygen levels first rose in Earth's atmosphere. This shows that biological utilization of oxygen probably occurred at very low concentrations relatively swiftly after it was first available, and that there is a more than 400-million-year gap in which sterols were probably being produced, but not preserved—the oldest sterols in the rock record are only about 1.6 billion years old. Mapping similar patterns in other genes lacking such a clear time-calibrated record is the continuing focus of this research activity, and has required substantial development of computational tools to take into account the uncertainty of evolutionary histories in specific genes, to accurately estimate their patterns of transfer and loss between lineages.

Honors and Special Activities

Ongoing awards to the laboratory this year include the Simons Foundation Collaboration on the Origin of Life and a collaborative award from the NSF's Integrated Earth Sciences program. A supplemental award to the Simons Foundation award was received to support an additional postdoctoral researcher or graduate student. The Fournier Lab also received the Charles E. Reed Faculty Initiatives Fund Award to support a graduate student research project on reconstructing the evolutionary history of carbon fixation cell machinery in the evolution of photosynthetic microbe lineages over the past two billion years.

During the fall 2016 semester, Gregory Fournier was co-instructor, with Alan Grossman of the Biology Department, for 7.493 Microbial Genetics and Evolution. Currently, Fournier's component of this subject is being redeveloped as a standalone offering in EAPS in fall 2017, 12.090/12.S492 The Phylogenomic Planetary Record. In spring 2017, Fournier taught a fully developed subject built on a previous spring 2016 special topics subject 12.177 Astrobiology: Origins and Early Evolution of Life. This subject is now a permanent addition to the EAPS offerings and an elective for the planetary science and geobiology tracks within the department.

Timothy Grove

Professor Timothy Grove, with graduate student Alex Mitchell, completed an experimental investigation of melt-wall rock reaction during melt transport in subduction zones. They were the first such experiments to rigorously recreate the process that occurs when deeper, hotter mantle melts ascend into shallower, cooler parts of the mantle wedge and interacts with that mantle. An important control on the melt-wall rock reaction is the proportion of melt that infiltrates. When the percentage of melt added is greater than 20%, the resulting reaction leads to the production of wehrlite, a rock type common in exposed mantle rocks. Until this work, which provides an explanation of how these rocks might form, the formation mechanism was enigmatic.. The temperature of the overlying mantle also exercises a crucially important control. Over a small temperature range (< 80^{o} C), melt-wall rock reaction can lead to the generation of the entire spectrum of mantle rock types, from depleted dunite to refertilized lherzolite—in other words, the entire spectrum of rock types found in mantle sections exposed around the world.

Honors and Special Activities

Professor Grove gave several invited seminars in AY2017. At Washington University in St. Louis, MO, he was invited to be the lecturer at the annual Larry Haskin memorial symposium. At Arizona State University's School of Earth and Space Exploration, he was invited to give their SESE Colloquium.

Teaching Activities and Institute Service

From August 19 to August 27, Grove led the EAPS Yellowstone trip, with 35 people attending. In the fall, he taught three subjects: 12.108 Structure of Earth Materials, 12.001 Introduction to Geology, and a freshman advising seminar, 12A03 Meteorite from Mars Kills Dog. In the spring, he taught 12.480 Thermodynamics for Geoscientists and a special reading group in 12.109 Undergraduate Petrology.

Grove continued as associate department head in AY2017, when EAPS implemented a new curriculum that the department hopes will make Course 12 more attractive to students deciding on their majors. The department also stepped up recruiting by contacting admitted MIT freshmen prior to orientation and inviting them to the EAPS building for information and conversation.

Other Service and Community Outreach

Professor Grove continued to serve on the American Geophysical Union's Development Board and is now chair of AGU's Centennial Steering Committee. In September 2016, he served as the chair of a NASA review panel for cosmochemistry. He is a member of the Joint Committee for Marine Geology and Geophysics in the MIT/Woods Hole Joint Program, stepping down as chair in November 2016. Grove continued as a member of MIT's Future of the Libraries Task Force in AY2017. He also continues to serve as executive editor for *Contributions to Mineralogy and Petrology and as an editor for the Proceedings of the National Academy of Sciences*.

Thomas Herring

Professor Thomas Herring is using primarily global positioning system (GPS) data to develop geophysically based models of Earth deformations on global, regional, and local scales, and of changes in the rotation of the Earth. He is also using interferometric synthetic aperture radar to study small surface deformations and geodetic methods to study Earth's gravity field. His group is using high-precision GPS measurements in many different study areas, including over much of the southern Eurasian plate boundary and the western United States. They are investigating processes (on a time scale of years) leading up to earthquakes, transient deformation signals lasting days to many weeks, post-seismic deformation after earthquakes (on time scales of days to decades), surface wave propagation during earthquakes using high-rate GPS data, and ice dynamics. All of these measurements have a precision of submillimeters to a few millimeters. The group is also monitoring and modeling human-induced deformations in hydrocarbon fields and on tall buildings, including the Green Building at MIT.

John Marshall

During academic year 2017, Professor John Marshall and his research group continued several lines of research. Marshall has ongoing projects in the Arctic, the Antarctic, and the Southern Ocean, and on the dynamics of the inter-tropical convergence zone (ITCZ). He is particularly excited by studies that explore the role of the ocean in mediating ITCZ shifts. This has led to a collaboration with Professor David McGee and an excellent PhD dissertation project by Brian Green. Graduate students Brian Green and Mukund Gupta are progressing well with their theses. Professor Marshall will take on a new graduate student in the fall.

David McGee

The research of Assistant Professor David McGee and his group continues to focus on understanding the response of precipitation patterns in past climates in order to offer insight into the sensitivity of the hydrological cycle to climate change. In academic year 2017 they offered important new insights into the history of the North African climate, documenting large-scale changes in windblown mineral dust emissions from the Sahara Desert that both trace local aridity and may amplify regional precipitation changes by reducing sea surface temperatures over the tropical North Atlantic Ocean. This work is a part of a larger effort to understand the patterns and drivers of past changes in tropical precipitation and the Hadley cell. They continue to use lake and cave deposits to trace past precipitation changes in poorly documented regions in the southern hemisphere, such as Madagascar and central Brazil, and they have recently received NSF funding to extend their work reconstructing past lake level changes in the Central Andes of Chile and Bolivia. The group has also just submitted a manuscript compiling data from around the tropics that identifies a consistent pattern of changes in the trade winds and Hadley cells—a pattern that accompanied past changes in the position of the tropical rainbelt. This manuscript provides a broad template for understanding past tropical precipitation changes and also identifies an important mechanism by which trade wind changes damp the magnitude of tropical rainbelt shifts, effectively limiting the range over which the rainbelt can move.

Academic year 2017 was Professor McGee's second year as the director of the Terrascope freshman learning community. The approximately 45 students in the community focused on the challenge of making cities more sustainable and resilient. He taught the fall subject 12.000 Solving Complex Problems and led a spring break trip to Mexico City.

He also worked with Terrascope staff to strengthen the program's spring term design course and initiated partnerships with the Environmental Solutions Initiative and D-Lab.

McGee led a multi-institution drilling project in the Searles Basin of Southern California to reconstruct past precipitation changes in the Owens River system, a major source of drinking water for the Los Angeles metropolitan area. A graduate student and postdoctoral researcher were involved in this field work as well.

Professor McGee's group sponsored activities at the Cambridge Science Festival and at the Carlson lecture at the New England Aquarium. More than 100 children and their parents learned about the study of past climate change and its relationship to questions of future climate change as a part of these events.

Shuhei Ono

Associate Professor Shuhei Ono studies the abundance of a doubly substituted isotopologue of methane ($^{13}CH_3D$) to identify the sources of methane in the environment, including swamps, natural gas, and hot springs in Iceland and on the sea floor. Methane on the Earth is largely produced by microbes. This new approach will help develop ways to test if methane on other planets and their moons could have been produced by microbes.

Shuhei Ono was awarded the Paul Gast Lectureship in 2017 from the European Association of Geochemistry and the Geochemical Society. In addition, he served as chair of the Joint Committee on Chemical Oceanography of the MIT/WHOI Joint Program.

Matej Pec

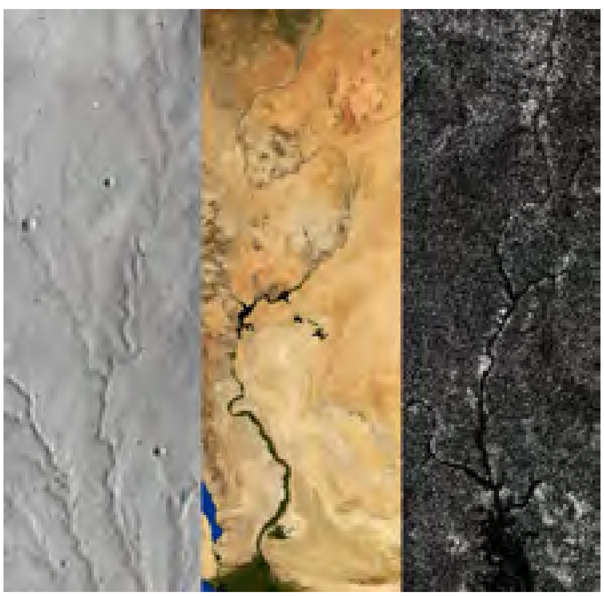
Assistant Professor Matěj Pěc joined the Department of Earth, Atmospheric and Planetary Sciences in January 2017 and has dedicated most of his time to starting up his experimental rock deformation laboratory. The laboratory space renovations required frequent meetings and consultations to make sure that everything was built to specifications. The lab space has passed all inspections and was open for use by the end of May. Professor Pěc welcomed his first postdoctoral associate, Hamed Ghaffari, in early June, and they have since installed their main research tool in the laboratory—a solid medium deformation apparatus capable of reaching up to 2.5 gigapascal confining pressure (about 80 km depth on Earth). They ran several calibration tests and familiarized themselves with the new equipment. Things moved forward swiftly toward the end of AY2017 with the main goal of getting the laboratory up and running.

Professor Pěc wrote and submitted two grant proposals; one, to the Charles E. Reed Faculty Initiatives program, was successfully funded. Pěc expects to equip the deformation apparatus with an array of piezoelectric transducers that will allow researchers to listen to the samples as they deform, as well as actively survey the microstructure during deformation with acoustic waves. This is an experimental approach; the initial funding allowed him to troubleshoot the design and generate preliminary results. The second proposal was submitted to the NSF's Division of Earth Sciences–Geophysics program with the goal of conducting a series of experiments that will clarify the influence of stress and strain on the melt network topology of partially molten rocks. Professor Pěc also helped with the writing of a postdoctoral proposal for the NSF with Cailey Condit, a PhD student in Boulder, CO. This proposal was funded and Cailey will be joining Pěc's laboratory next year as a postdoctoral fellow. Professor Pěc and Cailey are interested in investigating the rheological behavior of amphiboles—a common yet poorly constrained mid- to lower-crustal mineral.

J. Taylor Perron

Associate Professor J. Taylor Perron and his group study the processes that shape landscapes on Earth and other planets. Their efforts are focused on understanding widespread patterns in landscapes, climate's effects on erosion, and the landscapes of Mars and Saturn's moon Titan.

Titan's landscapes look similar to Earth's in many ways—rain-fed rivers have carved deep valleys into its surface. On Titan, though, the rain is liquid methane and the valleys are carved into ice. Perron's group has now discovered a way in which the landscapes of Titan and Mars are quite different from Earth's. River networks offer a window into the history of each world (Figure 1). Most topography on Earth is the result of plate tectonics, which builds mountain ranges that jut up and divert rivers as they flow toward the oceans. No one knows for sure what built the topography on Titan, but Perron and former graduate student Ben Black discovered that the rivers there have not suffered similar diversions. This tells us that the history of topography on Titan is less like that of Earth and more like that of Mars, where the large-scale features of the landscape were established first and then stayed more or less the same as rivers flowed across the surface and cut valleys. Along the way, Black, Perron, and colleagues confirmed that Mars did not have plate tectonics and show that river valleys on Mars mostly formed after the period of intense impact cratering had ended.



Images of river valleys on Mars (left), Earth (center), and Saturn's moon Titan (right).

Credit: Ben Black/NASA.

One of the major themes of Perron's research has been the influence of climate on erosion and landscape evolution. Perron recently summarized this research as well as the state of knowledge in the field of Earth sciences on the quantitative relationships between long-term climate and the erosion of Earth's surface. This review serves as a guide for understanding the past evolution of Earth's landscapes, the probable effects of future climate trends on erosion, and the most fruitful directions for future research on the topic.

Doctoral student Maya Stokes was awarded an Awards for Geochronology Student Research grant from the National Science Foundation Earthscope Program.

Paola Rizzoli

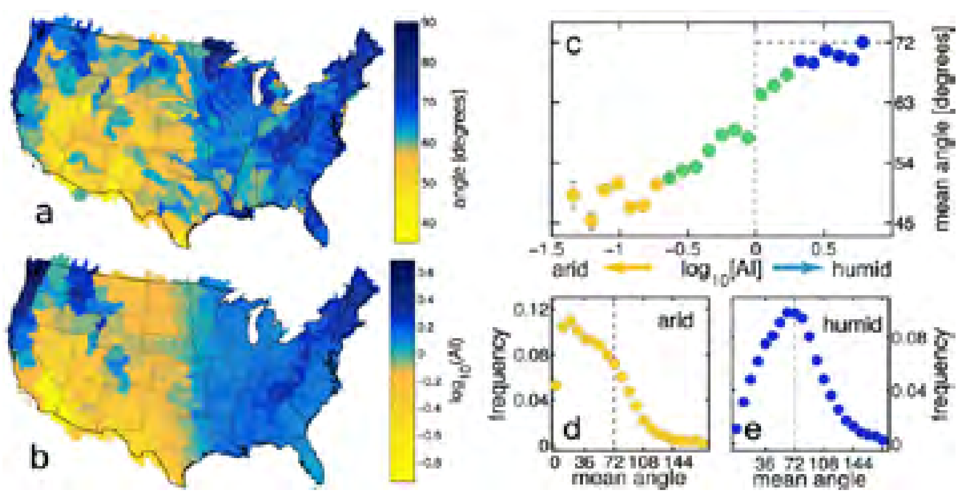
Professor Paola Rizzoli and her collaborators in the Center for Environmental Sensing and Modeling project of the Singapore–MIT Alliance for Research and Technology have continued to investigate the dynamical and thermodynamical changes in the South China Sea induced either by surface fluxes or boundary conditions. A further study has focused on the interactions between the South China Sea and the Indonesian throughflow and the consequent variabilities induced into the Sulawesi Sea.

In a collaboration with Professor Eltahir of the Department of Civil and Environmental Engineering, the researchers focused on investigating the exchange properties in the waters of the Singapore straits. The coupled atmosphere/ocean model developed for the Maritime Continent was applied in a way to allow for anthropogenically induced warming. Numerical simulations were carried out for the prediction of increasing temperatures and sea level rise by the end of the century under three different warming scenarios of the 2013 Intergovernmental Panel on Climate Change.

Professor Rizzoli was invited to submit an autobiographical paper for the 2017 *Annual Review of Marine Science*. The AGU selected her as the 2017 Rachel Carson Lecturer for the December 2017 AGU meeting.

Daniel Rothman

Professor of geophysics Daniel Rothman and his group have recently focused on two subjects: the stability of the carbon cycle and the effects of climate on landscapes. The latter research led to a publication earlier this year showing that river networks in humid regions bifurcate at wider angles than networks in arid areas. The characteristic junction angle in humid regions is consistent with the group's earlier theoretical prediction that networks growing in diffusive fields should ramify at angles of 2 pi/5 = 72 degrees. Groundwater flow, a ubiquitous presence wherever rainfall exceeds evaporation, provides the requisite diffusive field in humid climates Results are summarized in the accompanying figure. The group's work on the carbon cycle proceeds from the perspective of dynamical systems. Their most recent effort shows how disturbances in the carbon cycle at geologic timescales inform our understanding of the stability of the cycle at human timescales.



The influence of climate on the geometry of river networks. Parts (a) and (b) compare mean junction angles to an index (AI) of humidity throughout the conterminous United States. Part (c) shows that the mean angle approaches the predicted angle of 72 degrees as climates become more humid. Typical angle histograms are shown in parts (d) and (e). Reference: Seybold, H., D.H. Rothman, and J.W. Kirchner, "Climate's watermark in the geometry of stream networks," Geophysical Research Letters,*. 44, 2272–2280 (2017).*

Roger Summons

Members of Professor Roger Summons's geobiology laboratory continue to query geochemical records concerning early life and evolution on planet Earth. Collaborating with other researchers interested in these topics, they continue to advance knowledge about the environmental controls on the production of diagnostic lipids in modern organisms and settings, and their meaning for interpreting ancient fossilized counterparts.

A signature result came from a study led by postdoctoral associate David Gold together with former MIT undergraduate Abigail Caron and EAPS faculty member Gregory Fournier. The researchers used a phylogenomic and molecular clock approach to show that the sterol biosynthetic pathway—essential for the evolution of all complex life on Earth—most likely originated about 2.4 billion years ago, concurrently with geochemical evidence for atmospheric oxygenation.

In a study that looked at the possible preservation of organic records on Mars, Mary Beth Wilhelm and others showed that hyperarid, only poorly habitable environments can still be excellent candidates for the search for ancient life, provided appropriate steps are taken to avoid contamination. The group also published two studies concerning the correlations between the occurrence of certain bacteriohopanepolyols (bacteria-specific lipids) and environmental redox conditions. A third study reported the creation of a mutant cyanobacterium that is unable to make a class of methylated bacteriohopanepolyols and the effects of that mutation on adaptation to environmental stressors. This research was funded by grants from NASA, NSF, and the Simons Foundation Collaboration on the Origins of Life.

Robert D. van der Hilst

Professor Robert van der Hilst has been head of Department of Earth, Atmospheric and Planetary Sciences since January 2012. His research continues to focus on the following topics:

- Regional tectonics in Southeast Asia and North America
- Imaging of Earth's deep interior using dense seismograph arrays, in collaboration with Visiting Professors Maarten De Hoop (Rice University) and Michel Campillo (University of Grenoble, France), and colleagues at Imperial College London
- Development of algorithms for high-resolution seismic imaging with natural earthquakes (in collaboration with Professor De Hoop)

In the past year, Professor van der Hilst's team developed a method for determining contrasts in mass density and seismic wavespeed across interfaces deep in Earth's interior. From such measurements, they estimated the composition and temperature beneath the Central Pacific at depths that are well outside the reach of direct observation and measurement. Further, they presented a novel approach to high-resolution imaging of the structure of Earth's crust, the rocky outer part of the Earth on which we live, and demonstrated that one can use seismic waves to detected and quantify deformation of a volcano due to tides and changes in precipitation and atmospheric temperature.

Jack Wisdom

Professor Jack Wisdom has been working in a number of areas. During the 1980s and 1990s, Wisdom developed an integration method for studying the evolution of planetary systems. This method, now popularly known as the Wisdom-Holman method, is the basis for most long-term integrations of planetary systems and small bodies in the solar system. It is also known as the method of symplectic integration.

Recently, Wisdom has made several improvements in the method. First, he developed a new method to rapidly advance Keplerian orbits (one body orbiting a fixed center). The Kepler advancer is a key component in the Wisdom-Holman method. In this effort he collaborated with Physics graduate student David Hernandez. The new method is fast and accurate and works for all types of orbits. Second, Wisdom extended the Wisdom-Holman method to include the scattering and collisions of small bodies with massive planetary bodies. Wisdom used these new methods to carry out a study of the delivery of meteorites from the asteroid belt to Earth.

It has been observed that about twice as many meteorites fall in the afternoon as in the morning—the so-called afternoon excess. In the late 1970s, George Wetherill studied the evolution of meteorite orbits, using approximate methods, and deduced that there was an undiscovered source of Earth-crossing orbits in the middle of the asteroid belt. In the early 1980s, Wisdom found that chaotic resonances in the middle of the asteroid belt could pump up meteorite eccentricities to the point of making the meteorite Earth crossing. In 1985, as an assistant professor in EAPS at MIT, Wisdom first proposed that meteorites follow a chaotic route to Earth. Thus Wetherill's previously undiscovered source was now discovered.

In the late 1990s, there was a study that simulated the evolution of meteorites from chaotic resonances in the asteroid belt using the Wisdom-Holman method, and from these simulations estimated the fraction of meteorites falling in the afternoon to those falling in the morning. This study was unable to reproduce the afternoon excess, so the authors concluded that the afternoon excess was an observational artifact and that the Wetherill-Wisdom story was invalid.

In academic year 2017, Professor Wisdom revisited this problem with his new simulation methods. He found that meteorites are indeed delivered from the asteroid belt by way of chaotic resonances. He also estimated the afternoon excess for several different chaotic resonances and found that the observed afternoon excess was almost exactly reproduced. Thus, the study in the late 1990s that found conflicting results was shown to be incorrect, and the error in that study was identified.

Robert D. van der Hilst
Department Head
Schlumberger Professor of Geosciences