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GEOPHYSICISTS

Harmon Craig (1926–2003)

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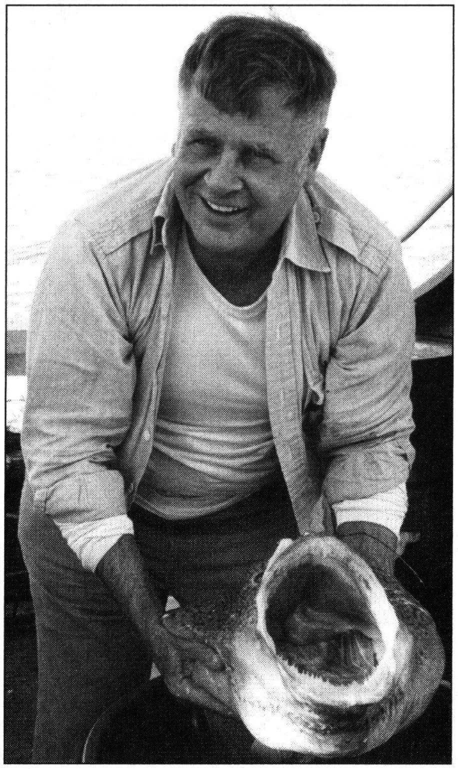
Harmon Craig, one of the great pioneers of isotope geochemistry, died on 14 March after suffering a massive heart attack at his home in La Jolla, California. He was one day shy of his 77th birthday. Through an academic career of more than fifty years, Craig—or simply "Harmon," as he was known throughout the world of geochemistry—made a remarkable number of fundamental and far-reaching contributions in a wide range of important areas concerned with the chemical and physical processes by which the solid Earth, the oceans, the atmosphere, and the solar system interact. While his research was broad in scope, it was also characterized by a strong emphasis on meticulous field and laboratory work, and on original and insightful interpretations of the resulting observations.

Early in his career, as a doctoral student in the laboratory of Nobel Laureate Harold C. Urey at the University of Chicago, Craig established the field of carbon isotope geochemistry by characterizing the stable isotopic signatures of carbon in ocean water, atmospheric carbon dioxide, plants, coal, petroleum, sediments, igneous rocks, diamonds, volcanic gases, and meteorites. He went on to study the relationships of stable and radioactive carbon isotopes in the biosphere and air-sea system, which later led to his derivation of the atmospheric residence time of carbon dioxide with respect to oceanic uptake, and to the subsequent development of improved box and diffusion-advection models to elucidate the roles of physical and biological processes in controlling the distributions of carbon and radiocarbon in the deep oceans. Collectively, this work forms the foundation of modern isotopic studies of the global carbon cycle, and thus plays a fundamental role in current efforts to understand and predict the roles of the oceans and the terrestrial biosphere in sequestering anthropogenic carbon dioxide; and thus, in modulating global warming.

With Urey, Craig showed that chondritic meteorites occur in discrete compositional groups with different oxidation states and different iron/silicon ratios. This provided the basis for what is now known as the Urey-Craig chondritic meteorite classifications, and for the subsequent quantitative study of major and trace element distributions in these meteorites. Craig later extended this work to stony meteorites and to studies of the thermo-dynamics of iron and magnesium distributions in meteorites.



Harmon Craig (above) during DSRV Alvin diving expedition to Loihi Seamount.

In 1955, Craig was brought to the Scripps Institution of Oceanography (SIO) by its director, Roger Revelle, where he expanded his work on stable isotopes to include the study of the global water cycle. He established the Meteoric Water Line, which defines the unique linear relationship between hydrogen and oxygen isotope ratios in natural terrestrial waters. He also discovered the oxygen isotope shift in geothermal and volcanic fluids, which showed (contrary to prevailing ideas) that the water in these fluids is overwhelmingly meteoric in origin. This work provided the basis for studies of water-rock interactions in geothermal systems and in hydrothermal vents. Craig also discovered the kinetic isotope effects in evaporation and molecular exchange. In a classical study, he provided the foundation for the application of isotopic studies to the study of the roles of evaporation, freezing, and exchange in the formation of ocean water masses, as well as for the study of paleoclimatology using the stable isotope record in polar ice.

In the 1960s and 1970s, he turned his interests to applications of geochemical tracers in oceanography, and he became one of the leaders of the GEOSECS program, the first integrated chemical, isotopic, and hydrographic study of the world's oceans. The measurements carried out by this program were of unprecedented accuracy and geographic coverage, and the data they produced now provide a benchmark for the study of changes in the hydrographic, chemical, and isotopic properties of the oceans resulting from climatic change and anthropogenic impacts. Craig's work on lead and uranium series isotopes in sea water led to a general model for the scavenging of trace elements by sinking particulate matter. Craig and his students also studied the isotopic compositions of atmospheric and dissolved oxygen and variations in the composition of dissolved gases. This work led to a method for determining biological oxygen production and consumption in the ocean mixed layer, as distinct from physical effects, and thus, to a better quantification of biological primary production rates in the oceans.

A series of extremely important contributions stem from Craig's discovery, with W. B. Clarke and M. A. Beg of McMaster University, of "primordial" excess helium-3 from the Earth's mantle in the waters of the deep Pacific. This was attributed to the emission of mantle-derived volcanic gases by sea floor spreading along the East Pacific Rise. Studies of oceanic basalts, volcanic gases, and hot brines on the floor of the Red Sea also showed this helium-3 isotope anomaly. The discovery of primordial helium-3 by Craig and co-workers (and simultaneously and independently by I. N. Tolstikhin studying hot springs in the Kuriles) provided the first definitive evidence that the Earth is still degassing helium trapped since its formation. This work formed the basis for widespread studies of helium isotope anomalies in the ocean, volcanic rocks, gases, and the mantle.

The enormous sensitivity of ocean measurements to the injection of helium-3 at the sea floor made possible the definitive proof of the presence of hydrothermal vents at a sea floor spreading axis by Craig and his co-workers using a remote sampling system. This led to the first direct observations of these vents and their unique life forms from the Alvin submersible. This work was later extended to studies of helium-3 and volcanic gases in many regions of the world's oceans. Craig and J. Lupton mapped plumes of deep water enriched in hydrothermal helium-3 extending from the crest of the East Pacific Rise westward for thousands of kilometers, both south and north of the equator. These major advective features, which were not anticipated by existing models of the deep circulation, have since led to improvements in numerical ocean models.

Craig's work on helium isotopes also focused on the study of mantle heterogeneities and mantle outgassing as sampled in volcanic gases from subduction zones, volcanic arcs, and mantle "hotspots." In mantle hotspots and regions of rifting around the world, Craig and his students and co-workers showed that proportions of primordial helium-3 vary substantially compared to mid-ocean ridge basalts, reflecting a spectrum of mixtures among mantle components seen in ocean island and continental hotspot basalts. They also showed that the mantle contains primordial neon and hydrogen isotopes, a discovery which has further revised our views of early atmospheric history and Earth degassing.

Craig also made significant contributions to the study of the present atmosphere and its more recent history. He was one of the earliest workers to study gases trapped in glacier ice, and showed that atmospheric methane has roughly doubled due to human activities over the past 300 years. He was also one of the first to study the geochemistry of atmospheric nitrous oxide, and to work on the production, rate of increase, and isotopic budget of this natural and anthropogenic modulator of the Earth's protective ozone layer.

More recently, his work focused on the physics and chemistry of gases in polar ice cores, including pioneering work on the gravitational separation of gases and isotopes within the permeable firn layer, and on the gravitational separation of rare gas isotopes as a measure of firn temperatures and thicknesses. This work is fundamental to the reconstruction of past atmospheric composition and isotopic variations based on measurements of gases in polar ice, and plays an important role in continuing efforts to understand past climatic change.

Harmon had a remarkable ability to focus his energies on important problems. He was passionate about doing his own field work, sometimes in the world's most remote and inaccessible places. He made laboratory measurements of the highest standard. But his greatest strength came from the imagination and thoroughness with which he interpreted these observations. His curiosity was limitless and his enthusiasm for science and drive for scientific achievement were unparalleled. He stimulated and challenged many colleagues around the world, and he mentored a number of graduate and postdoctoral students who are now themselves scientific leaders.

Harmon's accomplishments earned him widespread recognition. He was a recipient of the Balzan Prize, the Vetlesen Prize, the V. M. Goldschmidt Medal of the Geochemical Society, the Arthur L. Day Medal of the Geological Society of America, and honorary doctorates from the University of Paris and the University of Chicago. He was also a member of the National Academy of Sciences and the American Academy of Arts and Sciences, and a Fellow of the American Geophysical Union. The Earth sciences community has lost a truly spirited adventurer and one of its greatest geochemists.

He is survived by his wife of 55 years, Valerie, three daughters, and four grandchildren.

—RAY WEISS, Scripps Institution of Oceanography, University of California, San Diego

FORUM

The Last Word

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This is the third in a series of essays on terms used in solar-terrestrial physics that are thought to be in need of clarification. Terms are identified and essays are commissioned by a committee chartered by Division II (Sun and Heliosphere) of the International Astronomical Union. Terminology Committee members include Ed Cliver (chair), Jean-Louis Bougeret, Hilary Cane, Takeo Kosugi, Sara Martin, Rainer Schwenn, Lidia van Driel-Gestelyi, and Joe Borovsky.

Writers are asked to review the origins of a term and its current usage/misusage. The main point is to open a discussion and inform the community. We solicit letters to Eos *on the following article by Ioannis Daglis on the term "magnetic storm," which is certainly one of the most venerable names in solar-terrestrial physics. In addition, we welcome suggestions to any committee member on other terms to address in this forum.*

Magnetic Storm—Still an Adequate Name?

The magnetic storm is the principal and most complex collective phenomenon in geospace. It involves the magnetic fields of the Sun and the Earth, as well as plasma originating in the solar and terrestrial atmosphere. Magnetic storms involve more than just the geomagnetic field, as the original perception suggests. They involve a variety of dynamic processes among which charged particle acceleration and electric current intensification are the most important. Is the name still adequate, or should we switch to something more general and wide-ranging, such as "space storms," or "geospace storms"?

Origins of the Name

The oldest printed record of "magnetic storms" that I was able to find appears in a letter published in *Annalen der Physik* written by the famous explorer, Alexander von Humboldt, to Paul Erman. I located this paper in the amazingly rich library of the Air Force Research Laboratory at Hanscom Air Force Base in Massachusetts with the kind help of Mike Heinemann.

The "last universal scholar in the field of the natural sciences" had described a night of impressive observations in Berlin during the night of 20–21 December 1806 [*von Humboldt*, 1808]. Von Humboldt witnessed the appearance of an extraordinary auroral display and a concurrent, strong magnetic deflection of the magnetic needle that lasted for 6 hours. Two remarks of von Humboldt outline his perception of the phenomenon, which is quite far from the modern perception. First, he considered the geomagnetic deflection to be an effect of the aurora. Even more impressive is his second remark that, during this time interval, "there was no magnetic storm," as "the fluctuations were not especially intense" ("Dabei fand kein magnetisches Ungewitter statt; die Schwankungen waren nicht besonders stark"). This shows that although von Humboldt may have been the father of the name, he is certainly not the father of the magnetic storm concept; he used the term to describe intervals of intense magnetic fluctuations rather than a prolonged worldwide weakening of the horizontal component, *H*, of the geomagnetic field. This, of course, is to be expected, as there was no way for him to know about worldwide negative *H*-excursions.

Sydney Chapman, one of the great pioneers and founders of modern solar-terrestrial research who led much of the early work on magnetic storms, had noted that the term "magnetic storm" was a 19th-century innovation [*Chapman*, 1962]. In particular, *Chapman* [1967] clearly credits von Humboldt: "It was found that the greatest disturbances, which Humboldt called magnetic storms, begin nearly simultaneously all over the Earth, and that disturbance generally reduces the daily mean value of the horizontal intensity." However, it seems that in the 19th and early 20th centuries, scientists used "magnetic storm" for periods of intense geomagnetic variations in general, and not for what we perceive as magnetic storms nowadays. *Birkeland* [1908], for example, used the term "magnetic storm" to collectively describe five distinct types of magnetic perturbations (see details in *Chapman and Bartels* [1940]).

The morphology of the magnetic storm as we perceive it today emerged from a discussion of the long series of magnetic data from Bombay, India, by the Indian scientist Nanabhoy Ardeshir Framji Moos, director of the Colaba-Alibag Observatories. Although it had generally been known [e.g., *Broun*, 1861; *Adams*, 1892] that for some time after a period of great geomagnetic disturbance, the *H*-component of the geomagnetic field is reduced below its mean value, this critical information became much more complete through the work of Moos, which was decisive for recognizing the now-familiar storm pattern in the time variation of *H* [*Moos*, 1910]. Later, *Chapman* [1919] applied Moos' methods to study the average features of moderate storms at many stations in different geographic latitudes; he demonstrated the global aspect of magnetic storms and named the storm-time variation of *H* "Dst variation," meaning "disturbance storm-time." The characteristic average variation of Dst led Chapman to regard the storm geomagnetic variations as a unity with a beginning, middle, and end.

Apparently, Chapman was the one who combined the method and the name in his seminal statistical work and established the present concept of magnetic storm (S.-I. Akasofu, pers. commun., 2003). Starting with space flight in the 1960s, charged particle observations in space were gradually added into the "grande picture" of magnetic storms, complementing geomagnetic observations. Nevertheless, the name of this complex phenomenon remained "magnetic," or, alternatively, "geomagnetic,"