next 100 years. For national adaptation planning to be properly targeted, we must achieve competency in predicting regional climate changes through a better understanding of regionally specific climate processes.

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PERSPECTIVES: PLANETARY SCIENCE

What Is the Moon Made of?

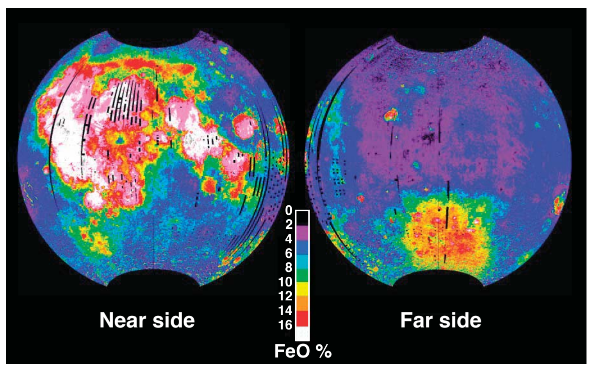
Paul D. Spudis

The Moon, long a most mysterious object, has in the past decade come under close scrutiny from orbital spacecraft. In 1994, the Clementine mission mapped its global topography and color (*1*). Four years later, the Lunar Prospector spacecraft mapped its chemistry and gravity from a lower orbit (*2*). These missions have greatly advanced our understanding of the global distribution of elements and rock types at the lunar surface. A picture of the Moon's structure and history is emerging that challenges some long-held views and confirms others.

Before the two orbital missions, knowledge about lunar surface chemistry was largely based on samples brought back by the Apollo and Luna missions. These samples showed that the Moon's highlands are rich in aluminum and poor in iron and magnesium (*3*). The new data confirm this picture on a global scale, with some subtle but important variations.

Huge regions of the highlands are extremely low in iron (see the figure). These regions are believed to be composed of an aluminum-rich rock type called anorthosite, the only low-iron rock type found on the Moon. Anorthosite forms when molten rock crystallizes slowly, allowing low-density, aluminum-rich minerals to float to the top of the magma body. The abundance of anorthosite in the highland crust strongly supports the notion that the Moon's outermost layer was once nearly completely molten, forming a "magma ocean" (*3*).

The isotopic composition of lunar anorthosite samples indicates that the magma ocean must have occurred early in



Global distribution of iron on the Moon. These maps are derived from Clementine color images by using the ratio of the 950- and 750-nm images and empirically calibrating the results against the "ground truth" supplied by the Apollo and Luna samples (*8*, *9*). The iron distribution is expressed as percentage of FeO in weight. Large regions of the Moon are very low in iron, supporting the magma ocean model for crustal formation. The large quasi-circular area of elevated iron content on the far side is the South Pole–Aitken basin, the largest known impact crater in the solar system. The elevated iron in this area, and the corresponding low-iron zone surrounding the basin rim, suggest that the lower crust of the Moon is exposed in the basin floor and is more iron-rich than the upper crust.

the Moon's evolution, while the Clementine data show that it was a global event. The only known source of sufficient heat for such an event is very rapid accretion, as expected if the Moon formed as a result of a giant impact between Earth and a massive asteroid (*4*). The global iron data provided by the Clementine mission thus support both the model of the lunar magma ocean and the popular giant impact model for lunar origin.

Much of the highland surface is iron-poor, but some zones appear enriched in iron, especially the floor of the huge South Pole–Aitken basin, a 2600-km-diameter impact structure centered on the southern far side (see the figure). The basin floor material is also enriched in titanium and the trace element thorium (*5*). In contrast to the iron-rich basin floor, the surrounding highlands are high in aluminum and low in iron.

These observations suggest that the large impact stripped off the upper aluminous crustal layer, exposing iron-rich material underneath. The lunar crust may thus be stratified, with a lower crust that is richer in iron, titanium, and thorium and less anorthositic than the upper crust. Such a crustal structure, combined with evidence from the Apollo samples, supports the idea that the Moon has a complex igneous history, with crust-forming magmatic events after the magma ocean had ceased to exist.

Basaltic volcanism is responsible for the lunar maria—the dark, smooth plains that fill ancient basins on the Moon. This volcanism must have occurred after the magma ocean had solidified. Mare volcanism is caused by the remelting of iron-rich cumulate rocks, deep in the lunar mantle (below 400 km). Volcanism was active from 4.3 billion years ago to at least 3 billion years ago (the youngest basalts in the Apollo collection); unsampled lavas may date from less than 1 billion years ago (*3*).

Clementine and Lunar Prospector data show that the titanium content of the maria varies by over an order of magnitude. The very high-titanium mare basalts first returned from the Moon by the Apollo 11 mission over 30 years ago turn out to be rare, although they are abundant in Mare Tranquillitatis (sampled by Apollo 11). Impact craters that penetrate the iron-rich

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mare basalt, thereby excavating the underlying iron-poor highlands substrate, show that most mare plains are quite thin, usually just a few tens of meters.

The global data from Clementine and Lunar Prospector allow us to assess the regional and global distribution of the different types of mare basalt. By measuring the density of impact craters in the maria and comparing it with the ages of sites sampled by Apollo, we can map the stratigraphy of the maria globally and determine their composition, thickness, and age. This will provide a more thorough knowledge about the history and intensity of volcanism on the Moon than we have for any other terrestrial planet, including Earth, for which most volcanic resurfacing (in ocean basins) is only partly understood.

The two missions also led to the startling discovery that water ice occurs in the permanently shadowed regions near the poles of the Moon (*6*, *7*). The Moon is extremely dry—lunar samples contain no water or even hydrous minerals. Water and ice are not stable on the Moon because of the high temperatures and the lack of an atmosphere. However, ice can be trapped at the poles in zones of permanent shadow. The polar water must have been added to the Moon from an external source, probably from impacting water-bearing meteorites and cometary nuclei. The deposits thus record the history of impacting volatile elements and compounds in the inner solar system for at least the past 2 to 3 billion years.

Our knowledge of the polar deposits is, however, sketchy. Details of the amounts, composition, and physical nature of the deposits may result from future missions, which may use orbital radar imaging to measure ice extent, thickness, and purity and surface in situ measurements to determine the chemical, isotopic, and mineralogical composition of the deposits.

The global compositional data provided by Clementine and Lunar Prospector are set to revolutionize our thinking about the evolution of the Moon. Together with existing information from the Apollo and Luna samples and the 21 lunar meteorites, they are helping us to unravel the long and complex history of the Moon. The Moon is a touchstone for our understanding of the evolution of the terrestrial planets in general. Once the data are fully assimilated, many ideas and concepts in planetary science may require substantial revision.

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PERSPECTIVES: ASTRONOMY

Galaxy Clusters Reveal Their Secrets

Robert Braun

Hydrogen is the most abundant element in the universe, accounting for some 70% of the total mass in baryons (particles such as protons and neutrons that experience the strong nuclear force). In addition to being ubiquitous, the hydrogen atom acts as an electric and magnetic dipole, giving rise to radiation interactions that have enormous diagnostic value in observational astronomy.

The electric dipole of hydrogen has long been exploited in astronomy. Since the recombination spectrum of hydrogen was first calculated about 100 years ago (*1*, *2*), this radiation has been used to study emissions from energized regions and absorption by quiescent regions at ever greater distances. The emission line strength is directly proportional to the number of ionizing photons. Strongly irradiated regions, such as the central regions of quasars, can thus be detected even at extremely large distances. The current record holder is at a redshift of 6.28 (*3*). Light reaching us from this distance has traveled for about 95% of the age of the universe.

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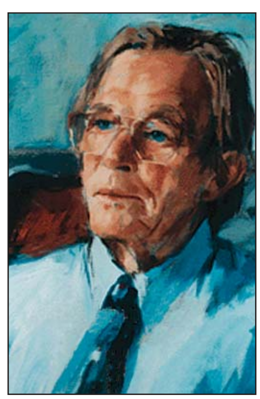
The magnetic dipole properties of hydrogen give rise to a much more subtle interaction. The tiny energy difference between parallel and antiparallel spins of the proton-electron system of atomic hydrogen corresponds to a radio photon with a wavelength at rest of 21.12 cm. Van de Hulst (see the first figure) predicted in 1945 that this transition might lead to an observable phenomenon (*4*). Soon after this prediction, the emission from atomic hydrogen clouds was detected in our own galaxy, the Milky Way (*5*). On page 1800 of this issue, 50 years after this first detection, Zwaan *et al.* (*6*) report the detection of the 21-cm emission of a galaxy comparable to our own at a redshift of 0.2. At twice the distance of the previous record, this corresponds to a light travel time of about 20% of the age of the universe.



Henk van de Hulst (1918–2000)

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The 21-cm magnetic dipole radiation of atomic hydrogen is so useful because under typical conditions, its line strength is directly proportional to the total number of hydrogen atoms in the source. The radiation is not obscured by interstellar dust particles, which strongly absorb light in the visible band but not at radio wavelengths. Furthermore, high spectral resolution can be achieved relatively easily at radio frequencies. The kinematics of galaxies other than our own can thus be determined routinely with great precision and out to large distances from the centers of these galaxies. These data have helped document reservoirs of gaseous atomic hydrogen, from which new generations of stars may form, under a wide variety of circumstances. Furthermore, they have shown that the rotation velocity of galaxies does not decline with distance from the center, indicating that galaxies must contain substantial amounts of dark matter (*7*).

The great drawback of the 21-cm emission line of atomic hydrogen is its intrinsic faintness. Today's optical and near-infrared telescopes, with diameters of 3 to 10 m, can be used to observe the hydrogen recombination lines from quasars at redshifts of 6 or more (*3*). In contrast, Zwaan *et al.*'s detection of the 21-cm emission from a normal galaxy at the comparatively modest redshift of 0.2 required more than 100 hours of observation with one of the largest current radio telescopes, with an equivalent diameter of almost 100 m (*6*).

The newly detected galaxy belongs to a massive galaxy cluster named Abell