solved much better than in previous observations (*7–12*), thereby enabling detailed comparison with the hydrogen absorption lines from the same structures in the optical spectrum of the same quasar.

Most hydrogen in intergalactic space is ionized. We know this because atomic hydrogen interacts so strongly with light at the Lyman-α wavelength that, if the intergalactic matter were not ionized, it would absorb all light at wavelengths shorter than the Lyman-α line at the redshift of the source. This is because the matter in front of the source is moving away from us less rapidly than the source.

The Lyman-α absorption seen in the spectra is caused by the tiny fraction of hydrogen that is atomic. This fraction is determined by a balance of the rate of photoionization due to the ultraviolet background light from galaxies and quasars, which ionizes the atoms, and the rate of proton-electron recombinations, which create new atoms.

The same process takes place with helium. A similar balance determines the fraction of helium in the form of He II. But the remaining electron in He II is much harder to strike out than in hydrogen, requiring photons with energies higher than the ionization potential of He II, which corresponds to wavelengths shorter than 22.8 nm. These photons are not produced abundantly by galaxies, whereas many more are produced with energies above the ionization potential of hydrogen, with wavelengths less than 91.2 nm. In addition, doubly ionized helium recombines much faster than hydrogen. As a result, there is much more He II than atomic hydrogen. The He II Lyman-α absorption is therefore stronger than that of hydrogen and reveals with greater clarity the matter in the regions of lowest densities.

The comparison of the He II and hydrogen absorption made by Kriss *et al.* allows them to probe for variations of the ratio of intensities at 91.2 and 22.8 nm in the radiation background that existed in the young universe when galaxies were forming and quasars were at their most active. If the ratio between these intensities were constant in space, then so ought to be the ratio of hydrogen and He II densities. As shown by Kriss *et al.*, there is evidence for significant fluctuations in this ratio and hence for variations in the ratio of background intensities at 91.2 and 22.8 nm. Moreover, they find these variations to be present on much smaller spatial scales than it was possible to probe before.

These background fluctuations are expected to be large when luminous sources, such as quasars, are the principal sources of emission because then only a small number of sources contribute to the overall radiation intensity at any given point in space (*13–15*). The presence of a nearby luminous quasar can then greatly change this intensity by different amounts at the ionization potentials of hydrogen and He II, explaining the fluctuations. The new results of Kriss *et al.* promise important insights into the role of quasars, galaxies, and perhaps other sources, as the originators of the far-ultraviolet background in the young universe.

References and Notes
1. J. E. Gunn, B. A. Peterson, *Astrophys. J.* **142**, 1633 (1965).
2. J. N. Bahcall, E. E. Salpeter, *Astrophys. J.* **142**, 1677 (1965).
3. M. Rauch, *Annu. Rev. Astron. Astrophys.* **36**, 267 (1998).
4. The redshift *z* of a source is defined so that 1 + *z* is the factor by which the received light's wavelength has stretched, that is, by which the universe has expanded since the light was emitted.
5. The Lyman-α photon is actually scattered out of the line of sight, but for the purpose of the observed spectra, this is referred to as "absorption."
6. G. A. Kriss *et al.*, *Science* **293**, 1112 (2001).
7. P. Jakobsen *et al.*, *Nature* **370**, 35 (1994).
8. A. F. Davidsen, G. A. Kriss, W. Zheng, *Nature* **380**, 47 (1996).
9. D. Reimers *et al.*, *Astron. Astrophys.* **327**, 890 (1997).
10. W. Zheng *et al.*, *Astrophys. J.* **492**, 855 (1997).
11. S. F. Anderson *et al.*, *Astron. J.* **117**, 56 (1999).
12. S. R. Heap *et al.*, *Astrophys. J.* **534**, 69 (2000).
13. L. Zuo, *Mon. Not. R. Astron. Soc.* **258**, 36 (1992).
14. L. Zuo, E. S. Phinney, *Astrophys. J.* **418**, 28 (1993).
15. M. A. Fardal, J. M. Shull, *Astrophys. J.* **415**, 524 (1993).
16. I gratefully acknowledge N. Gnedin for providing the figure and for his comments on the text.

The Origin of Water on Earth

Francois Robert

Some 4.55 billion years ago, the Sun and planets formed from the protosolar nebula, a rotating disk of gas and grains largely made of molecular hydrogen and helium. This disk is believed to have had a homogeneous isotopic composition from its center to its edge. However, the hydrogen isotopic composition of water on Earth differs widely from that of the primitive Sun. A deuterium/hydrogen (D/H) ratio of $(149 \pm 3) \times 10^{-6}$ has been estimated for the bulk Earth (*1*), compared with a solar ratio of $(20 \pm 4) \times 10^{-6}$ deduced from solar wind implanted into lunar soils (*2*) (see the first figure). This raises the problem of where the water on Earth originated.

A clue comes from carbonaceous meteorites, the most primitive objects of the solar system available for laboratory study. They contain two distinct hydrogen carriers: water, present in clay minerals, and or-ganic hydrogen, present mostly in macromolecular structures. Chemically extracted organic matter has shown a systematic enrichment in deuterium relative to Earth, with D/H ratios up to $(380 \pm 10) \times 10^{-6}$ (*3*). In contrast, the clays, which are associated at a submicrometer scale with the organic hydrogen, had a D/H ratio close to the terrestrial ratio (see the second figure) (*4*).

The deuterium enrichment in organic matter from meteorites has been interpreted as a relic of interstellar chemical reactions that took place shortly before the planets formed. Clay minerals in some rare meteorites also exhibit deuterium enrichment, with D/H ratios up to $(720 \pm 120) \times 10^{-6}$ (*5*). In analogy with the interpretation proposed for organic matter, the origin of solar system water has been ascribed to an interstellar process. However, we do not know the actual D/H ratio in interstellar ice. The detection of deuterated ice in interstellar clouds is technically very challenging, and measurements of the D/H ratio of interstellar ice in spectra obtained by the Infrared Space Observatory are still a matter of debate (*6*). A theoretical study suggests that ice grains synthesized at 10 K in the interstellar medium through ion-molecule reactions are highly enriched in deuterium, with D/H ratios up to 10^{-2} (*7, 8*).

Observations of comets further complicate the picture. As comets approach the Sun, water vapor sublimates. Spectroscopic studies of this water vapor have revealed D/H ratios of $(310 \pm 40) \times 10^{-6}$, substantially higher than that of terrestrial water (*9*). The contribution of cometary water to terrestrial oceans should thus be small (<10%). But what caused the D/H variations in the solar system water?

Modeling studies of the evolution of the protosolar nebula (*10*) indicate that once they had entered the nebula, interstellar ice grains vaporized and the D/H ratio of the resulting deuterium-rich water vapor was lowered through isotopic exchange with molecular hydrogen. As the temperature in the nebula decreased with time, the water vapor condensed into microscopic icy grains, with decreasing D/H ratios the closer they were to the Sun. This isotopic gradient reflects the fact that the closer to the Sun, the higher the temperature and the faster the isotopic exchange between water and molecular hydrogen. As the grains grew in size, their trajectories became independent of the turbulent

The author is at the Muséum–Minéralogie CNRS, 61 Rue Buffon, 75005 Paris, France. E-mail: robert@mnhn.fr
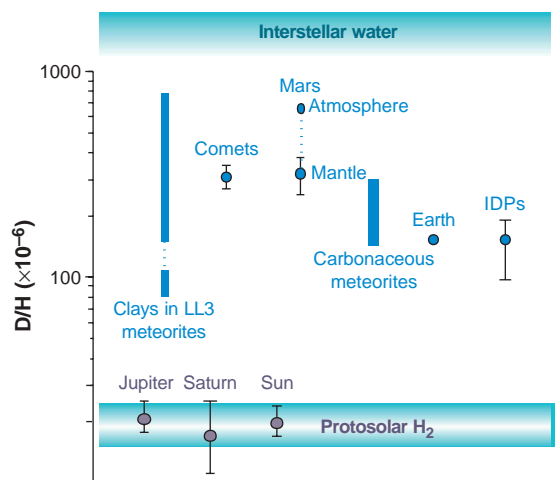
An isotopic enigma. Distribution of the hydrogen isotopic composition in solar system bodies. Blue, water; purple, molecular hydrogen.

movements of the gas and therefore the original isotopic gradient may have been lost in planetary size objects.

The models predict that the D/H ratio for water condensed at Earth's distance from the Sun should be close to the protosolar value, that is, $\sim 80 \times 10^{-6}$. But the ratio on Earth (149×10^{-6}) is markedly different from this value yet indistinguishable from clay water in carbonaceous meteorites. The terrestrial water must therefore have been imported from the coldest regions of the solar system after Earth had formed. But the exact conditions under which this addition was realized are unknown. It is particularly difficult to reconcile the collisional evolution of solar system planets with the geochemical records of the terrestrial atmosphere.

The present-day planets of our solar system are believed to result from collisional accretion of a myriad of primitive planets (from 10 km to several 1000 km in diameter), whose orbits around the Sun were unstable. Recent simulations (11) have shown that the addition of water-rich bodies during Earth's accretion may be responsible for a small fraction of water but that the main fraction was added by a few late giant impactors that may have contributed to Earth formation. According to the simulations, these impactors had D/H ratios analogous to those of the carbonaceous meteorites because they originated from the same cold region of the asteroid belts.

Although such a global scenario is compatible with hydrogen isotopic data, several issues remain unclear. First, as previously mentioned, the theoretical D/H ratio in interstellar ice (up to 10^{-2}) differs markedly from the highest measured values in the solar system (720×10^{-6}). Second, modelers predict that the protosolar nebula was hot, dense, highly turbulent, neutral, and mostly opaque

to ionizing radiation. Researchers studying the formation of disks around young stars argue instead that the protosolar nebula was cold, thin, transparent to ionizing radiation, and thus fully ionized (12). Third, astronomical observations indicate that intense ultraviolet fluxes emitted by newly formed stars can yield an interstellarlike chemistry at the surface of dense protostellar nebulae (13).

The water D/H ratios predicted for these different environments are quite different. Could it be that most of the low-temperature molecules (such as organics and water) of the solar system formed during such an initial period of intense ultraviolet fluxes and were then preserved in the cold, neutral, protosolar nebula? Protostellar nebulae are too small to be observed with present-day astronomical probes, and no coherent model exists for the progressive formation of protostellar nebulae from interstellar clouds. Hence, this issue remains a challenge for observation and theory alike.

It would help if we knew the D/H ratios of several water-bearing bodies in the solar system—such as the Jovian and Saturnian moons and the small icy bodies in the Kuiper belt beyond Neptune's orbit. Spectroscopic determinations during fly-by space missions above the surface of these satellites could record such isotopic information. The Kuiper belt objects are believed to be a source of microscopic grains drifting toward the Sun and are thus present among the interplanetary dust particles (IDPs) collected in the Earth stratosphere. Their recognition in IDP collections would allow the determination of the water D/H ratio in the most remote objects of our solar system, which will remain inaccessible to space missions for some time. These determinations will strongly constrain the chemical nature and the physical state of the protosolar nebula.
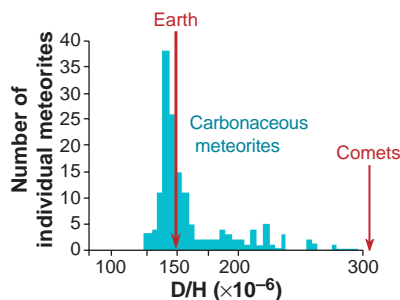
Meteorites represent the state of matter at the time of planetary accretion. If so, why is the isotopic signature of the protosolar molecular hydrogen not detected in these rocks? In other words, why are D/H

ratios close to 20×10^{-6} not measured in any minerals of the meteorites, despite the fact that the protosolar noble gases are still trapped in these rocks?

In some cases, hydrogen extracted at low temperature under pyrolysis from meteorites exhibits a deuterium-depleted signature, with a D/H ratio as low as 80×10^{-6} (14). Could this be the oxidized form (water) of the protosolar molecular hydrogen? If correct, do we have two sources of water in the solar system: an interstellar source and a protosolar one, the latter resulting from the oxidation of H_2 at high temperature? Detailed stepwise pyrolysis performed on individual minerals would be of a great value to revisit this question.

The question of the origin of water on Mars is also much debated, not least because it is related to the question of whether life ever existed on our red neighbor. On the basis of isotopic analyses of Martian meteorites, a D/H ratio of 300×10^{-6} has been ascribed to the mantle of this planet (15). If correct, this could imply a much larger contribution of cometary water on Mars than on Earth. It remains to be shown whether this scenario is compatible with the dynamical evolution of the small planets originally formed in the solar system. On Mars, water is photodissociated by the ultraviolet flux, and H, the lighter isotope of hydrogen, escapes to space at a much higher rate than D. The atmospheric D/H ratio is therefore much higher (810×10^{-6}) than that of the mantle (300×10^{-6}). The deuterium enrichment of the Martian mantle relative to that of Earth may therefore result from the recycling at depth of the deuterium-rich atmospheric water. Models of the dynamical evolution of the Martian interior can thus be constrained by the distribution of D/H ratios among different geochemical reservoirs of the planet.

Water from meteors. Distribution of the hydrogen isotopic ratio in carbonaceous meteorites compared with Earth and comets. According to this distribution, water on Earth seems mostly derived from a meteoritic source.

Most cosmochemists believe that silicates could not be altered in the nebula to form the clay minerals found in meteorites because the required alteration processes are prohibitively slow in the gas phase. Clay minerals in meteorites should therefore result from water circulation in the small planets that once hosted the meteorites. If correct, all hydroxylated minerals should have identical D/H ratios (within $\pm 5\%$) that reflect the isotopic homogeneity of the liquid water. This is clearly not the

case in deuterium-rich metorites, whose D/H ratios vary within less than 100 µm by more than 400%. How can a hydrothermal mechanism yield such results?

It is tempting to believe that the enormous isotopic heterogeneity in altered silicates predates the formation of the meteorites and thus was produced in the gas phase. This question must be addressed through laboratory experiments by measuring the alteration rate of amorphous silicates and by studying the far-infrared spectra of young stellar objects to search for the presence of clay minerals in circumstellar disks (*16*).

The use of the D/H ratio demonstrates a clear connection between the solar system and interstellar water. The search for its origin on Earth requires collaboration between different disciplines and represents an unique opportunity to reconcile astronomical and geochemical records.

References and Notes

1. C. Lecuyer *et al.*, *Chem. Geol.* **145**, 249 (1998).
2. J. Geiss, G. Gloecker, *Space Sci. Rev.* **84**, 239 (1998).
3. J. Halbout *et al.*, *Geochim. Cosmochim. Acta* **54**, 1453 (1990).
4. F. Robert *et al.*, *Space Sciences Series of the International Space Science Institute* (Kluwer Academic, Dordrecht, Netherlands, 2000), vol. 92, pp. 201–234.
5. E. Deloule, F. Robert, *Geochim. Cosmochim. Acta* **59**, 4695 (1995).
6. T. C. Texeira *et al.*, *Astrophys. J.* **347**, L19 (1999).
7. P. D. Brown, T. J. Millar, *Mon. Not. R. Astron. Soc.* **237**, 661 (1989).
8. L. d'Hendecourt, talk given at the conference on Deuterium in the Universe, Observatoire de Meudon, France, 25 to 27 June 2001; see wwwusr.obspm.fr/unicom/deuterium.
9. D. Bockelé-Morvan *et al.*, *Icarus* **193**, 147 (1998).
10. A. Drouart *et al.*, *Icarus* **140**, 129 (1999).
11. A. Morbidelli *et al.*, *Meteoritics Planet. Sci.* **35**, 1309 (2000).
12. Y. Aikawa, E. Herbst, *Astrophys. J.* **526**, 314 (1999).
13. A. E. Glassgold *et al.*, in *Protostars and Planet IV*, V. Mannings *et al.*, Eds. (Arizona Univ. Press, Tucson, AZ, 2000), pp. 429–450.
14. E. Deloule *et al.*, *Geochim. Cosmochim. Acta.* **62**, 3367 (1998).
15. L. Leshin, *Geophys. Res. Lett.* **27**, 2017 (2000).
16. K. Malfait *et al.*, *Astron. Astrophys.* **345**, 181 (1999).
17. I acknowledge stimulating discussions with J. Aléon, N. Dauphas, E. Deloule, L. Leshin, B. Marty, J. Eiler, Y. Aikawa, D. Bockelé-Morvan, L. d'Hendecourt, E. Herbst, F. Hersan, D. Gautier, T. Owen, and T. Millar at recent conferences.

PERSPECTIVES: PROTEIN SYNTHESIS

Believe It or Not—Translation in the Nucleus

Matthias W. Hentze

The nucleus is the principal defining feature of eukaryotic cells. The genetic material of the cell is stored in the nucleus and is transcribed into mRNAs, which are then processed and exported to the cytoplasm. So the orthodoxy goes, once in the cytoplasm mRNAs are "read" by rotund factories called ribosomes and are translated into proteins. That transcription and translation take place in two different cellular compartments distinguishes eukaryotic cells from bacteria, which do not have a nucleus. This spatial separation protects cells from the deleterious effects of making faulty proteins, which could happen if incompletely processed mRNAs were to be translated in the nucleus. This "separatist" view is now challenged by Iborra *et al.* (*1*), who report on page 1139 of this issue that mRNA translation also takes place in the nucleus.

The concept of nuclear translation is not entirely new. Earlier studies showed that a small fraction of amino acids are incorporated into polypeptides in the nucleus. However, many attributed this finding to cytoplasmic contamination (*2*). More recently, structures with the biochemical and pharmacological characteristics of polyribosomes have been described in the nuclei of the slime mould *Dictyostelium* (*3*). This work, however, did not indicate

The author is in the Gene Expression Programme, European Molecular Biology Laboratory, Meyerhofstrasse 1, D-69117 Heidelberg, Germany. E-mail: hentze@embl-heidelberg.de

whether these structures were unambiguously localized in the nucleus or whether they carried out protein synthesis. Although these earlier reports of nuclear translation were greeted with skepticism, it is now accepted that most components of the translation machinery are present in

the nucleus. For example, the two ribosomal subunits are assembled in the nucleolus, translation initiation and elongation factors reside in the nucleus, and even the addition of amino acids to transfer RNAs (tRNAs) by aminoacyl–tRNA synthetases can take place in the nucleus (*4–6*). But the question is, can these separate components unite and orchestrate protein synthesis in the nucleus?

In their study, Iborra *et al.* adopted a strategy that would enable them to visualize nuclear protein synthesis. They pinpointed nuclear sites of translation by labeling permeabilized mammalian cells or purified nuclei with fluorescent lysine. The accumulation of nuclear fluorescence was time dependent and sensitive to inhibitors of eukaryotic protein synthesis (cycloheximide and puromycin), but not to the bacterial translation inhibitor chloramphenicol (see the figure). The authors estimate that nuclear translation accounts for about 10 to 15% of protein synthesis in the cell.
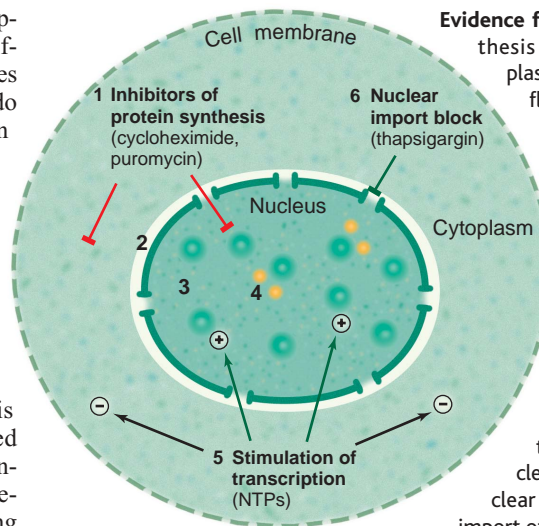
Evidence for nuclear translation. (1) New protein synthesis in the nucleus (green dots) and the cytoplasm—as indicated by nuclear and cytoplasmic fluorescence after incorporation of fluorescent lysine—is equally sensitive to inhibitors of eukaryotic translation. (2) Isolated nuclei show no detectable extranuclear or perinuclear fluorescence, indicating that proteins made in the cytoplasm are not being imported into the nucleus. (3) Purified nuclei display undiminished intranuclear fluorescence. (4) Nuclear translation sites are not randomly distributed, but overlap with sites of gene transcription as indicated by immunogold labeling (yellow dots). (5) Stimulation of transcription by increasing the concentration of nucleotides enhances nuclear but not cytoplasmic fluorescence. (6) Nuclear fluorescence is not affected by blocking the import of proteins into the nucleus by thapsigargin.

Iborra and colleagues put forward several arguments in support of their claim that the nuclear fluorescence they observed truly represents protein synthesis in the nucleus and does not result from the import of proteins made in the cytoplasm (see the figure). First, they performed their experiments under conditions that allowed the incorporation of only a few amino acids into the proteins being synthesized.