PERSPECTIVES: ASTRONOMY

Water's Role in Making Stars

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The water molecule plays a fundamental role during the first stages of star formation. It is an important oxygen reservoir in the warm environments of star-forming regions and is believed to contribute substantially to the cooling of the circumstellar gas, thereby helping to remove the excess energy accumulated during protostellar collapse.

Water may be present in a star-forming region either as a gas or as ice on the surface of dust particles. The relative abundance of gas to ice depends on the physical and chemical characteristics of the environment and can thus be used as a diagnostic to probe different stages of stellar evolution—but only if the molecules can be detected. This has turned out to be difficult with ground-based instruments, thus hampering the verification of chemical models of star formation.

Water vapor has an extremely rich spectrum from the submillimeter to the near-infrared wavelength range, caused by the wide range of rotational and vibrational excited states accessible to the molecule. (This feature makes water a particularly efficient coolant because many channels are available for emitting photons after a collision, thereby converting thermal energy into light.) Unfortunately, detection of these lines from Earth is completely blocked by the water vapor in the atmosphere, even at the high altitudes reached by aircraft and balloons. In recent years, this problem has been overcome by two space missions, the Infrared Space Observatory (ISO) (*1*), which ended its activity in 1998, and the Submillimeter Wave Astronomy Satellite (SWAS) (*2*), which has been operating since the beginning of 1999. ISO detected many water transitions between 3 and 200 μm for the first time and was able to detect absorption features on the continuum spectrum of background sources that are specific to icy water. SWAS is specifically designed to measure the water content in cold molecular clouds (where stars are born) through the observation of the H_2O transition at 539 μm that is excited at temperatures as low as 40 K.

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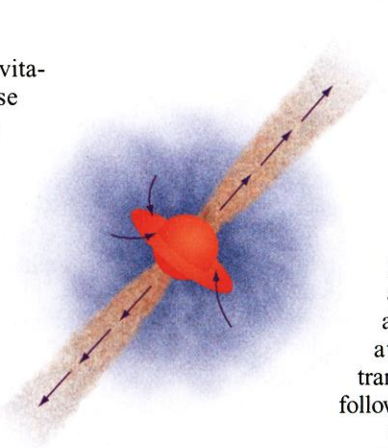
Stars form from gravitational collapse of dense molecular clouds. At the beginning of this process, the cloud is very cold (with temperatures of around 10 to 30 K), and almost all the water is located in the icy coats of the dust grains. Some water is, however, produced in the gas phase through a series of reactions that start from H_3^+ and O and result in the formation of H_2O and O_2. Current chemical models for cloud evolution predict a water abundance of 10^{-6} to 10^{-7} with respect to molecular hydrogen (*3*), but abundances estimated from SWAS observations in different clouds are about 10 to 100 times lower (*4*). The reasons for this discrepancy remain unclear, but both models and observations indicate that gaseous water is an insignificant component in the cloud before protostar formation.



Water everywhere. A large amount of water vapor is produced in the circumstellar envelopes heated by the accretion energy of the infalling material and in the strong radiative shocks driven by the violent bipolar jets ejected from the central protostar.

As gravitational collapse proceeds, the radiation energy released by the accretion of matter onto the newly born protostar is absorbed by the dense and thick circumstellar envelope, which quickly heats up as a result. At the same time, protostars also violently eject mass in the form of bipolar jets, which transport the excess energy and angular momentum away from the central object (see the first figure).

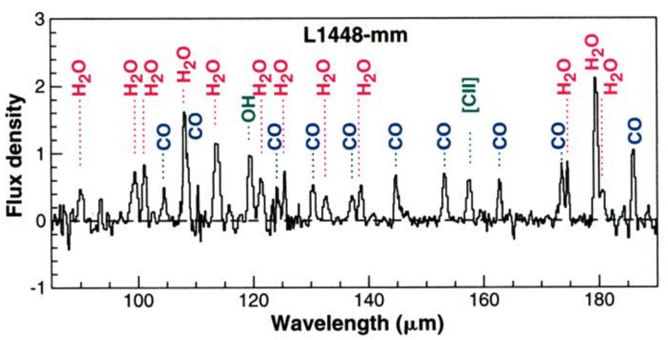
When the jets encounter the dense ambient medium, they produce strong shock waves that can increase the gas temperature up to a few thousand kelvin. In such warm environments, two processes are expected to produce water very efficiently (*5*, *6*). As the temperature of the dust grains rises above about 90 K, their ice coats release water by evaporation. Moreover, at gas temperatures above about 300 K, all the available atomic oxygen is rapidly transformed into water by the following reactions:

$$O + H_2 \rightarrow OH + H \quad (1)$$

$$OH + H_2 \rightarrow H_2O + H \quad (2)$$

Under these conditions, water is expected to increase in abundance by several orders of magnitude compared with the cold clouds and to become the most abundant species after molecular hydrogen. Because molecular hydrogen is an inefficient coolant, water can give a comparable or even larger contribution to the overall cooling in the warm gas.

ISO was able to confirm these expectations for the first time. It detected a large amount of warm gaseous water in active star-forming regions such as the cluster of protostars inside the Orion BN region, which shows a very strong and complex water spectrum originating both from shocked gas and from the hot core surrounding the cluster (*7*). The inferred water abundance exceeds 10^{-4} relative to molecular hydrogen, thus confirming that large amounts of gas phase water are produced once the protostar is formed.



Detection of water in star-forming regions. The Infrared Space Observatory (ISO) enabled the first direct observation of emission by water in precursors of stars like the sun. Shown here is the spectrum from 100 to 200 μm of one of these protostars [adapted from (*8*)]. The spectrum is dominated by strong lines of water and carbon monoxide. Line emission from the hydroxyl radical (OH) and ionized carbon is also observed.

ISO detected water lines not only in high-mass, luminous young stellar objects but also in low-luminosity protostars, which are precursors of stars like our sun (see the second figure). These systems often show high water abundances, not only close to the protostar but also along the bipolar flows, suggesting that H_2O is mainly produced in shocks (*8*). In spite of that, however, cooling due to water is never dominant in shock models; H_2 and CO always appear to be more important cooling species. This discrepancy must be resolved by further refining the current models if we want to understand the energy balance of the protostellar system.

As protostellar evolution proceeds, the circumstellar matter is gradually dispersed and the power of the outflow declines, but some of the original cloud material remains present in the form of a circumstellar disk. Gas excitation by the star's radiation field increasingly leads to the dissociation of water into OH and atomic oxygen, following the reverse reactions of Eqs. 1 and 2, over large regions (*9*). In dense circumstellar disks, however, part of the water produced during star formation can be deposited on dust grains, resulting in an enrichment of the disk material with water ice. In this form, water can remain unaltered until the disk evolves into a protoplanetary system, which may eventually form solid planetary bodies. ISO and SWAS could not measure the water content of protoplanetary systems because of insufficient spatial resolution; they were restricted to investigating regions no smaller than a few thousand astronomical units (AU) (1 AU is the distance between the sun and Earth) from the central star.

The ISO and SWAS observations of water in different environments during star formation have allowed chemical models of star formation to be tested for the first time. Instruments with higher spectral and spatial resolution will become available with space missions planned over the next decade, such as the Far Infrared and Submillimetre Telescope (FIRST) and the Next Generation Space Telescope (NGST). These missions may lift some of the remaining mysteries, particularly regarding the later stages of stellar formation, and may even provide insights into the likelihood of the development of life, which is crucially dependent on the availability of water.

References and Notes

1. See *Astron. Astrophys.* **315** (no. 2) (1996) for a special issue on the first ISO results.
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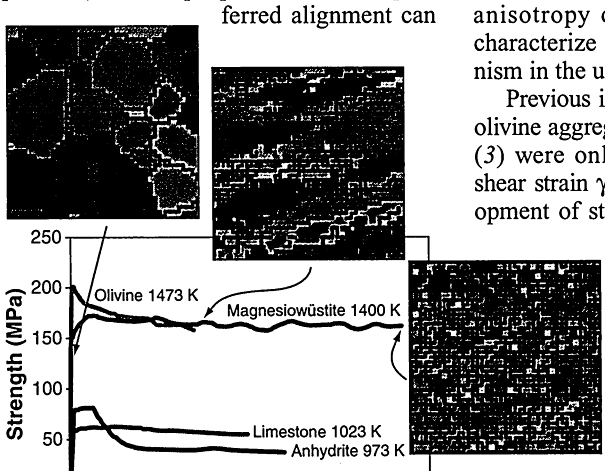
PERSPECTIVES: GEOPHYSICS

Earth Under Strain

Stephen Mackwell and David Rubie

Heat is constantly transferred from Earth's hot interior to the surface through convection of the mantle. At Earth's surface, mantle convection drives plate tectonics, as manifested by earthquakes, volcanoes, and mountain building. When the slowly convecting mantle encounters regions that are less mobile, for example, at the bottom of the rigid plates, substantial amounts of shear strain may accumulate. On page 1564 of this issue, Bystricky *et al.* (*1*) illustrate how rock textures and mechanical behavior evolve during this type of deformation. The results can be correlated with measurements of seismic wave propagation through the mantle, providing fundamental insights into processes occurring in Earth's upper mantle.

Seismic waves travel through Earth's interior as compressional waves, where the particle motion is parallel to the propagation direction of the wave, or shear waves, where the particle motion is perpendicular to this direction. When shear waves are detected at the surface, they can be resolved into two components at right angles to each other. Numerous seismological studies have demonstrated that in the shallow mantle below the oceans, the component of shear waves parallel to the direction of plate motion is often faster than that perpendicular to that direction (*2*). The difference in velocity leads to shear-wave splitting, such that one component arrives at the seismic station in advance of the other. This different behavior for parallel and perpendicular waves is due to the preferred crystallographic alignment of minerals that have anisotropic (direction-dependent) elastic properties. Such a preferred alignment can be induced during plastic deformation by dislocation creep, where motion of crystal dislocations along planes in the mineral grains results in straining of the rock (*2*).



Unexpected behavior. Rocks composed of different minerals show substantial variation in mechanical behavior and textural evolution when deformed to high strains in simple shear. The plot shows evolution in strength of the various rock types with increasing shear strain. Data from (*1, 6-8*). The digital scanning electron microscopy images of the grain texture of magnesiowüstite samples show evolution of microstructure with increasing strain. The images are 250 μm wide.

As Bystricky *et al.* (*1*) show, shear deformation of a rock composed predominantly of olivine, the major upper mantle mineral, results in a preferred orientation of one particular crystallographic axis parallel to the shear direction. This observation is consistent with seismic observations of shear-wave splitting in the oceanic upper mantle. The new results (*1*), however, also demonstrate that use of the seismic anisotropy data alone cannot uniquely characterize the dislocation creep mechanism in the uppermost mantle.

Previous investigations of the textures in olivine aggregates during shear deformation (*3*) were only performed to a maximum shear strain γ of 1.5, too low for the development of steady-state textures and deformation behavior. The powerful experimental technique applied by Bystricky *et al.* (*1*) applies a torsional stress to the sample, allowing shear deformation to large strains (*4*) that appear to reproduce mantle temperatures and strains reasonably well (although the strain rates are too fast). This approach has been used to investigate the high shear strain behavior of rocks composed of olivine (*1*), marble (*5*), limestone (*6*), anhydrite ($CaSO_4$) (*7*), and magnesiowüstite [(Mg,Fe)O] (*8*). The textural and mechanical evolution of rocks made of these minerals with increasing shear strain is quite varied (see the figure). Limestone (*6*) shows little change in strength or texture and continues to deform even at high strains by diffusional creep, where diffusion of atoms along

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