PERSPECTIVES: PLANETARY SCIENCE

A New Look at the Jovian Planets

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The Infrared Space Observatory (ISO) (*1*), launched in November 1995 by the European Space Agency (ESA), provided a great opportunity for solar system research. During its 2.5-year lifetime, ISO has extensively studied planets, satellites, comets, asteroids, and zodiacal light with its four focal-plane instruments. The arrival of Comet Hale-Bopp, in particular, provided a unique opportunity to study the properties of cometary gas and dust at large distances from the sun (*2*). These results were recently presented at meetings held in Madison, Wisconsin, and at UNESCO in Paris, France (*3*).

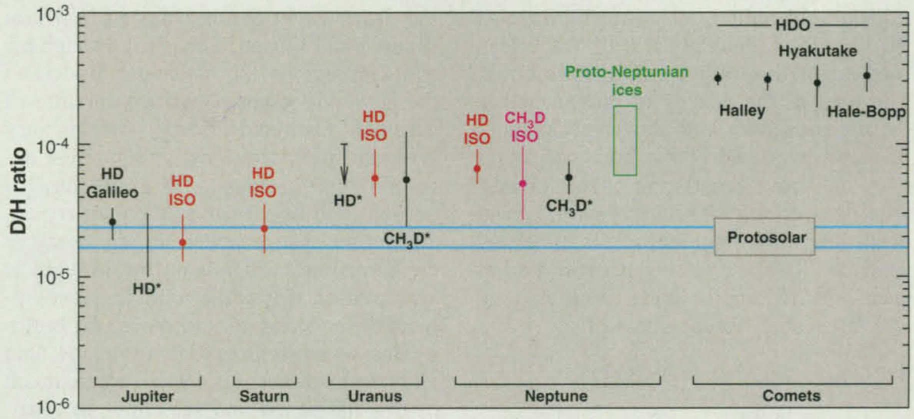
Saturn

The jovian planets (Jupiter, Saturn, Uranus, and Neptune) were observed by the two ISO spectrometers in the entire 2.3- to 180-μm wavelength range. The Short Wavelength Spectrometer (*4*), in particular, obtained spectra below 45 μm with a resolving power of about 1500 in the grating mode and 30,000 in the Fabry-Perot mode and at unprecedented sensitivity.

Deuterium was formed in the early universe by primordial nucleosynthesis and was later burned in stars; the value of the deuterium/hydrogen (D/H) ratio in the protosolar nebula thus provides a clue to cosmological models. The jovian planets are believed to have formed from the accretion of a central icy core and the capture of gas from the surrounding protosolar nebula. In the case of Jupiter and Saturn, this core represents a small fraction of their total mass, so that the D/H ratio in their atmosphere is expected to be representative of the gaseous component of the protosolar nebula. Uranus and Neptune, in contrast, have more than half of their mass contained in their ice-rich interior, where deuterium is thought to have been enriched by ion-molecule or molecule-molecule reactions at low temperature in the nebula; the D/H ratio in their atmospheres is thus expected to be higher.

ISO has provided a new determination of D/H in the four giant planets through the first detection of HD rotational lines. In the case of Jupiter and Saturn, the derived D/H ratio, close to 2×10^{-5} (*5*), is in agreement with the recent D/H value in Jupiter given by the Galileo probe (*6*) and is consistent with independent estimates of the protosolar value. The D/H ratio is larger on Uranus and Neptune (about 6×10^{-5}) (*7*), in agreement with current models of planetary formation. From this result, it is possible to infer the D/H value in the ices that formed the cores of Uranus and Neptune. The result is about 1×10^{-4}, substantially smaller than the D/H measured in comets (3×10^{-4}), which has important implications for models of cometary formation (*8*) and of the solar nebula (see figure).

Halley



Primordial clues. D/H ratios in the solar system derived from measurements in various molecules: deuterated water (HDO) in comets and deuterated methane (CH_3D) or HD in the jovian planets. Asterisks indicate ground-based measurements. [Figure adapted from (*8*)]

Hydrocarbon photochemistry in the jovian planets is initiated by the photolysis of methane (CH_4), the most abundant carbon species in their atmospheres. Its photodissociation in the upper atmosphere results in the production of simple hydrocarbon species such as ethane (C_2H_6), acetylene (C_2H_2), and ethylene (C_2H_4). These compounds themselves undergo photolysis and can produce higher order hydrocarbons through complex reaction schemes. Although CH_4, C_2H_6, and C_2H_2 have been observed from infrared spectroscopy for over 20 years (except on Uranus), ISO detected for the first time methyl acetylene (CH_3C_2H) and diacetylene (C_4H_2) on Saturn (*9*), as well as benzene (C_6H_6) on both Jupiter and Saturn [benzene had previously been detected on Jupiter (*10*), but only in a region of intense auroral activity near 70°N].

Jupiter

These detections are important because they show that methane photochemistry can produce substantial amounts of complex hydrocarbons. Benzene and diacetylene may in addition be important components or precursors of the stratospheric hazes present on these planets. These observations will motivate photochemical studies and laboratory measurements as the chemical schemes leading to these hydrocarbons, especially benzene, are not yet fully understood.

On Uranus, ISO detected C_2H_2 but not CH_4 despite the high sensitivity of the instruments. Combined with photochemical models, these observations allow us to set precise constraints on the eddy mixing rate in the stratosphere and confirm that mixing is much less vigorous on Uranus than on Jupiter, Saturn, or Neptune.

Spectral measurements with ISO also led to the detection of the methyl radical (CH_3) in Saturn and Neptune (*11*), the first radical ever observed in a planetary atmosphere. CH_3 radicals are directly produced by photodissociation of methane and mostly lost by self-recombination to form ethane ($CH_3 + CH_3 \xrightarrow{M} C_2H_6$). The methyl abundance depends on the strength of the atmospheric eddy mixing, which governs the location of the methane homopause where methyl is mostly produced and lost. These observations provide a diagnostic tool to constrain this poorly known parameter, still requiring laboratory measurements of the CH_3 re-

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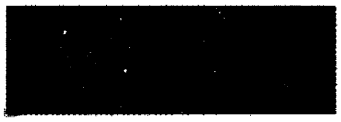
Hale-Bopp

combination rate at low temperature.

The detection by ISO of water vapor in the stratospheres of the four giant planets was unexpected on thermochemical grounds (*12*). Water, which is abundant in the troposphere, freezes out at the cold tropopause. What mechanism could be delivering water to these upper atmospheres? External fluxes implied by the observations are similar on all planets, on the order of 10^5 to 10^7 oxygen atoms per square centimeter. This similarity suggests that interplanetary dust is an important source. These observations may thus provide a means of estimating the production of dust, possibly from comets, at large heliocentric distances. Another possible source is micrometeorite erosion from either the rings or the icy satellites surrounding the planets.

In addition, a signature from CO_2 was seen on Jupiter, Saturn, and Neptune (*12*). On Neptune, this species could be supplied by the same external source as H_2O, if the CO_2/H_2O ratio in the infalling material is a few percent, as observed in cometary nuclei. But this source alone is not sufficient for Saturn. Another possibility is the formation of CO_2 by reaction of CO with OH radicals produced by the photolysis of H_2O. Within this framework, the nondetection of CO_2 on Uranus would result from a much lower abundance of CO in its atmosphere than on the other giant planets. On Jupiter, the limited spatial resolution of the ISO measurements allows us to infer that CO_2 is concentrated in the southern hemisphere and not detectable at high northern latitudes. This peculiar distribution suggests that the presence of CO_2 is a remnant of the collision of Comet Shoemaker-Levy 9 that struck Jupiter in July 1994 near 45° south latitude. The cometary impacts deposited large amounts of CO and H_2O in the upper atmosphere. As predicted by postcollision evolution models (*13*), CO_2 is subsequently produced by the reaction of CO with OH radicals.



Hyakutake

Observations of the solar system with ISO have gratified planetary scientists with a wealth of new findings. Although some measurements still need to be fully analyzed and understood, infrared astronomers are looking ahead to new opportunities, including NASA's Space Infrared Telescope Facility (SIRTF), scheduled for 2001, and the Far Infra-Red and Submillimetre Telescope (FIRST), an ESA cornerstone mission, planned for 2007.

References and Notes

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PERSPECTIVES: ECOLOGY

The Plankton and the Planet

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What determines how fast photosynthetic organisms in the oceans grow? The question is of crucial importance for understanding the global ecosystem. The phytoplankton are the base of the oceanic food chain, and thus their growth rate ultimately controls the biomass that the oceans can support. Furthermore, the phytoplankton make a major contribution to global oxygen production and carbon dioxide absorption. A world in which the phytoplankton grew a little faster, or a little slower, would be a very different place. On page 840 of this issue, Behrenfeld and Kolber (*1*) report some new information on the factors that limit the growth of the phytoplankton.

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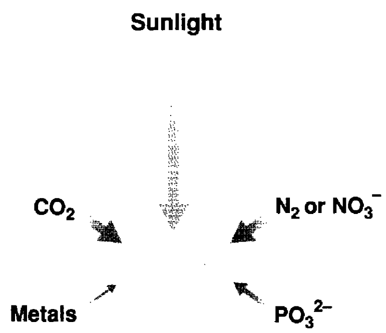
The phytoplankton are tiny, mostly single-celled, organisms. In the open oceans, the dominant species are prokaryotes, principally *Prochlorococcus* and *Synechococcus*. *Prochlorococcus* is usually present in far greater numbers [Behrenfeld and Kolber report 70,000 to 200,000 cells per milliliter (*1*)]. *Synechococcus* is a cyanobacterium (a blue-green alga). Molecular phylogenetic studies (*2*) show that *Prochlorococcus* is also a cyanobacterium, although it has an unorthodox pigment composition. In terms of sheer numbers, *Prochlorococcus* may well be the dominant organism on this planet, yet it was only recently discovered (*3*).



Essential ingredients. Raw materials required for growth of a marine photosynthetic organism. Materials that are essential but always abundant in seawater are not indicated.

The basic materials that phytoplankton need to build copies of themselves are relatively simple (see figure). They need sunlight as an energy source, water, and inorganic nutrients. Carbon is obtained by "fixing" carbon dioxide. Nitrogen may be obtained from nitrate; if this is unavailable, some cells will fix molecular nitrogen. Phosphorus and sulfur come from phosphates and sulfates dissolved in the seawater. In addition to these bulk constituents, the phytoplankton require trace nutrients. A number of metals, including iron, are required as essential cofactors of photosynthetic complexes and other proteins (*4*).

The growth rate of the phytoplankton depends on the supply of these raw materials. Their relative availability is vastly different in different environments. In the simplest case, one particular nutrient is limiting in any given environment. If the supply of the limiting nutrient were gradually increased, the phytoplankton would grow faster until something else became limiting. The factors that could limit growth in different marine environments include the amounts of iron (*5*), nitrate (*6*), phosphate (*7*), carbon dioxide, and light. Close to the surface, light is present in excess, and the ultraviolet component of sunlight can actu-

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