

PLANETARY SCIENCE

Neptune's Deep Chemistry

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independently at the eruptive vent should provide strong constraints on the flow in the conduit and then on the pressure in the magma chamber. Seismicity measurements have also been used to probe the magma reservoir; however, path and site effects make the information of what happens at depth difficult to unravel from the seismic signature (5).

The structure of air low in the atmosphere is simpler than that on the ground, and measurements of pressure in air can easily be made either with acoustic devices (usually for frequencies > 20 Hz) or microbarographs (< 1 Hz). Surprisingly, although the sound produced by a volcanic eruption is rather striking, only a few studies existed until a few years ago. Richards (6) observed that each type of volcanic activity emits a characteristic sound. Later, Woulff and MacGetchin (7) used the acoustic power radiated by an eruption to measure the gas velocity. Recent studies have shown that most of the acoustic energy is infrasonic (below 20 Hz), at least for basaltic volcanoes (8), although some information on the geometry of the volcanic system can be deduced from frequencies between 4 and 70 Hz (9). It is only today that the old network of microbarographs are used by Morrissey and Chouet to extract the exit pressure at the start of an explosive eruption and also to constrain the gas concentration in the volcanic column (1). Their study uses a low-frequency range for pressure waves in air (0.1 to 1 Hz) not explored before.

Such a method provides quantitative measurements of a key variable for understanding volcanic activity, at a low cost and remotely. This method could also be used to locate eruptions in difficult environments and to estimate eruption magnitude. In the future, by combining measurement of pressure waves in air with that of seismicity, one could hope to separate path and site effects from the seismic source at shallow depths. Furthermore, adding measurements of velocity at the surface, by visual observations whenever possible, will improve our understanding of what is happening at depth. These methods will help us to assess and mitigate the hazard related to explosive volcanoes.

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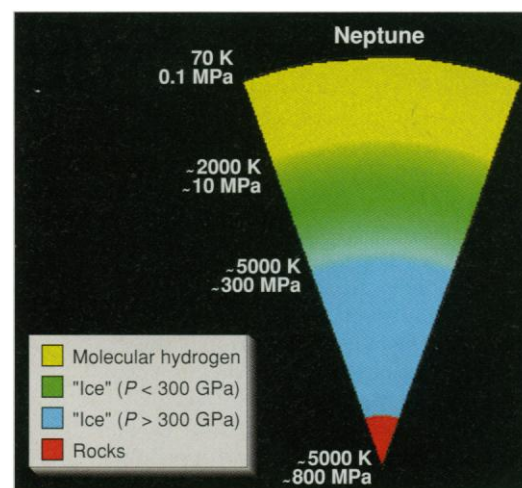
All four of the giant planets—Jupiter, Saturn, Uranus, and Neptune—have deep, massive atmospheres that superficially resemble the sun in composition (mostly hydrogen and helium). Yet they differ from the sun in that these atmospheres are composed of light molecules rather than thermally dissociated atoms. Thus, the composition of these atmospheres could well be modified by deep interior processes analogous to those familiar to terrestrial-planet geochemists. Giant-planet specialists have been aware for some time that in situ measurement of the composition of a giant planet's atmosphere, as was done for Jupiter's atmosphere by the recent Galileo probe (1), might need to be interpreted in terms of chemical processes in much deeper layers. Only recently have theory and experiment given specific results about the chemistry of relevant light molecules, such as H_2 , H_2O , and CH_4 , at pressures around $P = 100$ GPa. One such result is presented on page 1288 of this issue by Ancilotto *et al.* (2), who report simulations showing that some C_2H_6 in Neptune's atmosphere might come from deep within the planet.

In contrast to Jupiter and Saturn, the H_2 - and He-rich atmospheres of the two smaller giant planets Uranus and Neptune only reach pressures of perhaps 10 GPa and comprise only ~5 to 10% of the planetary mass. The mean densities of Uranus and Neptune and data from their gravity fields indicate that below the atmosphere is a vast ocean of hot (several thousand kelvin) H_2O , NH_3 , and CH_4 , which are in a dense liquid phase but are customarily denoted as ices (see figure). The fate of the methane in this "ice" region is of particular interest: Remote spectroscopic analyses of Uranus and Neptune's atmospheres have for some time indicated that the abundance of CH_4 relative to H_2 is at least 10 times larger in the smaller and denser giant planets Uranus and Neptune than in the more sunlike giant planets Jupiter and Saturn. Could this enhancement be a clue to the existence of a methane-rich ocean below the atmosphere?

Also seen in the spectra of Neptune are

the molecules C_2H_2 and C_2H_6 , which, according to conventional wisdom, are products of ultraviolet photolysis of abundant CH_4 in Neptune's stratosphere (3). The former is seen at a mixing ratio of about 0.01 parts per million (ppm), and the latter, at about 1 ppm. Ancilotto *et al.* (2) offer the interesting suggestion that some of this atmospheric C_2H_6 may actually be a quenched reaction product from much deeper layers in Neptune, analogous to the quenched CO seen in Jupiter (4).

Earlier, Ross (5) considered the fate of



Cross section of a typical interior model of Neptune (8); the interior of Uranus is predicted to be very similar. Ancilotto *et al.* predict that methane decomposes into saturated hydrocarbons in the upper "ice" layer.

methane in the deep interiors of Uranus and Neptune and concluded that at high pressures, the reaction would produce H_2 and pure C in the form of diamond crystals. The latter, if large enough, would irreversibly sink as sediment toward the center of the planet, whereas the hydrogen would rise to join the atmosphere. Estimates of the total mass of methane in Uranus or Neptune indicated that such decomposition would produce a significant but not dominant source of atmospheric hydrogen. In this picture, one would expect atmospheric methane to be depleted relative to solar abundance, not enhanced, so Ross's diamond-producing mechanism seemed to lack any observational confirmation.

The model of Ancilotto *et al.* (2) also predicts some dissociation of methane into free hydrogen molecules, but apparently to a lesser degree than in the diamond-forming

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mechanism of Ross. Whether products from chemical reactions at high pressures in Uranus or Neptune actually find their way into the observable atmosphere depends on the existence of deep-seated circulation patterns at the base of the hydrogen atmosphere and in the upper "ice" layer. Uranus is considerably less active than Neptune both from the point of view of atmospheric dynamics and interior heat flow. A possible diagnostic of communication between the atmosphere and the "ice" layer is the atmospheric abundance of deuterium relative to hydrogen, D/H. In the primordial icy objects in the outer solar system and in Earth's oceans, the D/H ratio is enhanced by nearly one order of magnitude relative to the primordial solar

composition (6). One expects that D/H in the Uranus and Neptune "ice" layers would also be enhanced by this factor, so exchange of hydrogen between the atmosphere and interior would lead to some enhancement of D/H in the atmosphere (7). Recent measurements of D/H give values lower than the predicted enhancement, suggesting incomplete communication between the atmosphere and interior, particularly in Uranus.

Our knowledge about chemical abundances in the atmospheres of Uranus and Neptune derives from the extended Voyager 2 mission and from Earth-based and orbiting observatories. In the case of Jupiter, comparisons between results from remote-sensing data and in situ data from the Galileo probe

caution us that abundances obtained from remote sensing must be interpreted with care and that entry probes will probably be needed for definitive determinations of atmospheric abundances in the giant planets.

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DEVELOPMENT

Left-Right Asymmetry

Elizabeth J. Robertson

On the surface, the left and right sides of our bodies seem perfectly identical. But appearances can be misleading. Closer inspection reveals that all vertebrates exhibit left-right (L-R) asymmetry in the positions of their visceral organs. A striking example is provided by the heart, which invariably loops to the right side. The molecular controls of this process are just coming into view; the latest player is reported on page 1301 of this issue (1).

Elegant experiments in the chick (2) have revealed that during L-R axis formation a number of signaling molecules are transiently expressed on only one side of the emerging midline of the embryo—including an activin receptor (ActRII), sonic hedgehog (Shh), and the transforming growth factor- β (TGF- β) family member nodal (see figure). This asymmetric pattern of gene expression precedes any tangible evidence of morphological L-R asymmetry. The very earliest signal appears to be mediated by ActRII positioned along the right side of the primitive streak shortly after the onset of gastrulation. This inductive cue is then relayed to lateral plate mesoderm cells as they migrate anteriorly from their origins in the streak and is reinforced by Shh and nodal expressed on the left side of the node. A few hours later, nodal becomes selectively expressed in a broad stripe of lateral plate mesoderm on the left side of the body axis. The primitive heart tube then begins its program of looping and bends to the right. A similar rightward rotation of the entire body axis closely follows.

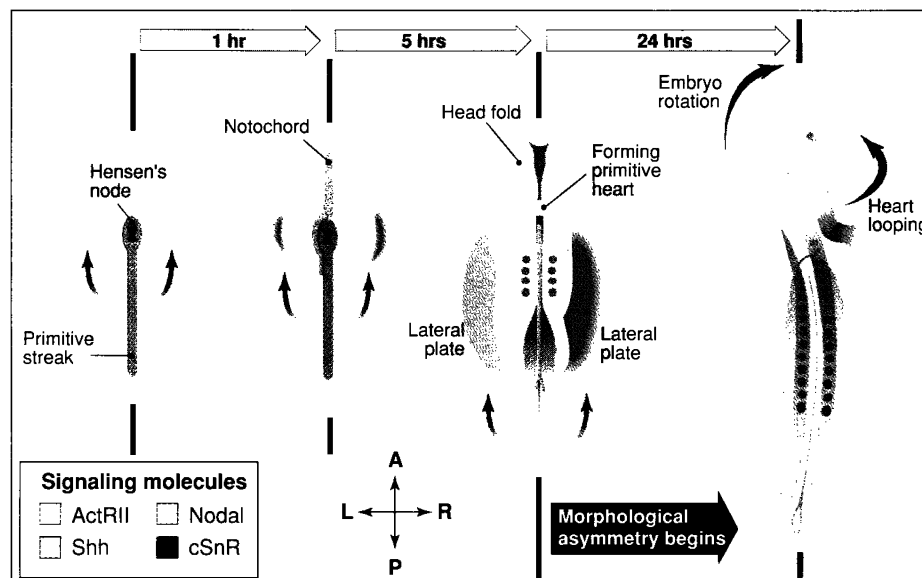
In this issue, Isaac and colleagues report that cSnR (for Snail-related), a new member of the Snail family of zinc finger proteins (1), is expressed in lateral plate mesoderm cells on the right side of the chick embryo, in a domain that roughly mirrors that of nodal on the left. Moreover, specific antisense oligonucleotides can down-regulate cSnR expression and randomize the direction of heart looping and axial rotation. Interestingly, this manipulation does not perturb nodal expression, indicating that cSnR acts downstream of nodal.

Does the same L-R pathway operate in other vertebrates? Nodal homologs are asymmetrically expressed in mouse (3, 4) and *Xenopus* (4). As in chick, nodal expression is

strictly confined to mesoderm populations on the prospective left side of the embryo. In both mouse and chick, alteration of the sidedness of nodal expression is sufficient to change both the direction of heart looping and embryonic turning (1, 3, 4). What could cSnR contribute to these morphogenetic processes? Perhaps nodal represses cSnR expression on the left side of the axis. Indeed, Isaac *et al.* show that perturbing the initial L-R cue with soluble activin randomizes expression of both nodal and cSnR in later stage chick embryos (2). Mutually exclusive patterns of nodal and cSnR expression could potentially activate distinct sets of downstream target genes. Hopefully these missing pieces of the L-R puzzle can soon be coaxed into view.

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