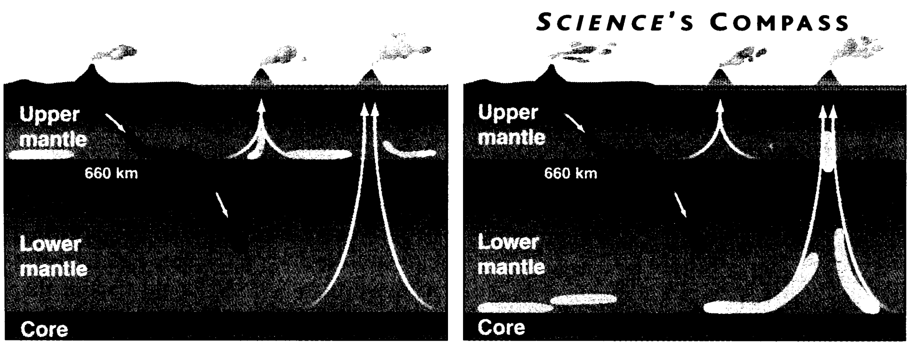

Models of mantle convection. (Left) In a two-layer convection model, the 660-km discontinuity serves as a barrier for convection. **(Right)** Alternatively, subduction of crustal material can reach the lower mantle before being transported upward again in a plume.

mechanism of mantle convection, at present and far back in Earth history. As discussed by Blichert-Toft, *et al.* (*5*), hafnium and neodymium isotopes are well correlated in most oceanic basalts. But some Hawaiian lavas have unusually radiogenic Hf isotopes given their Nd isotopic composition. Similar features are found in modern pelagic sediments, but not in most other types of crustal or mantle rocks. Blichert-Toft *et al.* also show that the lavas with the most unusual Hf isotopes derive from a source with a much higher Pb:Hf ratio than other Hawaiian lavas. This higher ratio is characteristic of crustal-derived sediments. These data strengthen previous suggestions for a recycled component in Hawaiian lavas (*11–13*). Blichert-Toft *et al.* further suggest that the low $^{207}Pb/^{204}Pb$ values in the recycled sediment compared with most modern sediments require that this sediment is ancient, perhaps as old as 3 billion years. It is not clear how robust this age estimate is, although other estimates using different assumptions or isotopic systems have also yielded ages greater than 1 billion years (*13*).

Depending on the depth at which the Hawaiian plume originates, the presence of old recycled crust in the plume suggests two different models of mantle convection. If the Hawaiian plume derives from the 660-km discontinuity, the presence of ancient recycled crust in the plume would suggest that this region of the mantle has acted as a slab "graveyard" for much of Earth history. This would strengthen suggestions that whole-mantle convection began recently (*4*). In contrast, if the Hawaiian plume derives from the core-mantle boundary, the presence of ancient crust in this plume would require such recycled material to be present in the lower mantle. This would in turn require that slabs penetrated the 660-km discontinuity at 1 to 3 billion years ago, much as they do today.

How can we determine the depth from which the Hawaiian plume originates? Geochemistry can provide only indirect evidence. Brandon *et al.* (*14*) recently argued that anomalous abundances of an osmium isotope, ^{186}Os, in some Hawaiian lavas reflect incorporation of a small quantity of core material. Blichert-Toft *et al.* argue that the Hf-Nd isotope trend in Hawaiian lavas precludes melting of depleted upper mantle. The lack of an upper-mantle signature in Hawaiian basalts may indirectly suggest that the Hawaiian plume originated at greater depth.

Seismological studies can potentially provide a stronger constraint on the Hawaiian plume's depth of origin. Recent seismological studies have shown that the Iceland plume extends through the upper/lower mantle transition zone (*15*) to the core/mantle boundary (*16*), providing the most direct evidence to date for some mantle plumes deriving from the core/mantle boundary. No comparable study has yet been performed for Hawaii. An extensive array of ocean-bottom seismometers will be necessary for detecting a hot, narrow plume in the deep mantle beneath Hawaii, if such a plume exists. Such a study, combined with the increasingly robust evidence for ancient recycled crust in the Hawaiian plume, may finally answer the question whether mantle convection is, or has been, substantially layered.

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PERSPECTIVES: PLANETARY SCIENCE & ASTRONOMY

Extrasolar Giant Planets and Brown Dwarfs

Adam Burrows

Until just 5 years ago, the census of stars in our galaxy did not extend much below one-tenth of a solar mass ($M_\odot$). An object of less than ~0.08 $M_\odot$ cannot sustain itself by thermonuclear burning against the inevitable radiation losses from its surface. Such substellar objects, nicknamed brown dwarfs, should thus radiate and cool over eons of astronomical time like hot coals plucked from a fire. These objects were expected to resemble large, hot planets such as Jupiter, but planetary scientists had only been able to detect and study planets in our solar system. That left a yawning gap between the mass of Jupiter (M_J), ~0.001 $M_\odot$ or 1 M_J, and that of small stellar objects with ~0.1 $M_\odot$, a gap of two orders of magnitude in mass in the distribution of known objects. Be they extrasolar planets formed in protostellar disks around bright and massive stars or substellar-mass brown dwarfs formed directly by the same processes that give rise to stars, they remained undetected, their existence in doubt, their importance debated, their properties unknown.

This situation has changed dramatically as recent surveys in the solar neighborhood, in young stellar clusters, and around nearby stars are turning up scores of giant planets and brown dwarfs. The optical brightness of stars like our sun makes it obvious that they at least are prevalent in the galaxy, but in the solar neighborhood, there may be more brown dwarfs than sunlike stars (*1*). Substellar objects are far less luminous and emit the bulk of their luminosity in the infrared. Direct photometric and spectroscopic measurements of brown dwarfs—previously beyond the powers of technology—are now writing a new chapter in stellar astronomy. The brown dwarf Gliese 229B (*2*) was the first in a series of discoveries. Since then,

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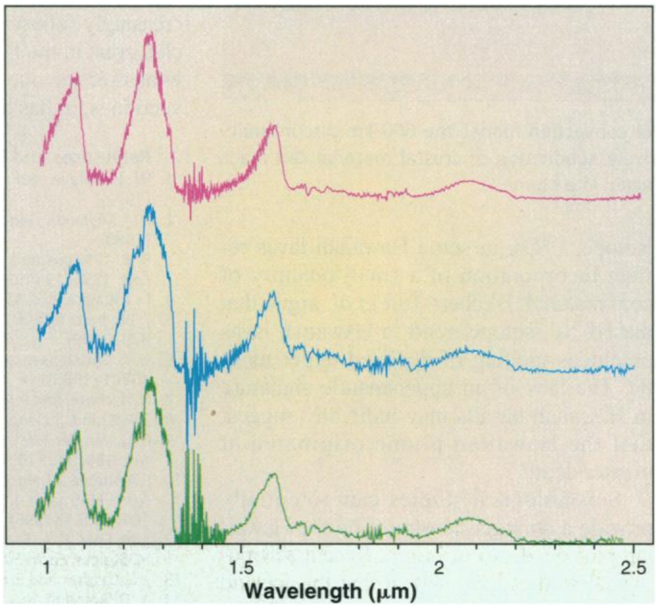
the first new stellar spectral type in almost 100 years, the "L dwarfs," has been discovered, with atmospheric compositions unlike those of any of the well-studied stars (*3*). Seven "methane" dwarfs, similar to Gliese 229B, with a hitherto unprecedented effective temperature (T_{eff}) of ~950 K, have been found (*2, 4*); the lowest T_{eff} for a star is ~1750 K. Four brown dwarf–brown dwarf binaries are now known (*5*). More than 20 giant planets orbiting nearby stars have been discerned through the Doppler wobble they cause in their parent stars (*6, 7*); some of these systems are multiples (*8*). Many extrasolar giant planets (EGPs) are 100 times closer to their parent stars (*6*) than Jupiter is to our sun, strongly suggesting that our planetary system is no guide to the diversity of planetary systems that populate the galaxy.

A recent workshop (*9*) illustrated the pace of discovery and showed how these discoveries are providing a link between planets and stars. In addition to the announcements of new objects, the participants learned of exotic atmospheres depleted by the rain-out of refractory metals, the bizarre importance of neutral alkali metals, the counterintuitive bluing of spectra with decreasing T_{eff} (*10*), and x-ray emission from cool L dwarfs. They also heard about layers of aerosols and rock clouds, reflection spectra of planets heated to ~1200 K by their primary stars, and stratospheres of phosphides, sulfides, and hydrocarbons.

The radius of an EGP or a brown dwarf is about one-tenth that of the sun. Being so compact, they are dense and their atmospheres are made up predominantly of molecules, not atoms. Molecular hydrogen and water dominate, but CO, CH_4, NH_3, FeH, CrH, and the nascent alkali metals Na, K, Rb, and Cs can play important roles. Strong water absorption bands define the spectral holes in the substellar atmosphere through which photons pour from its hot depths, with magnitudes in the near infrared (for example, around 1.2, 1.6, 2.2, and 5.0 μm) that are substantially above blackbody values. Water in Earth's atmosphere defines the windows through which astronomers can peer into space. Hence, the presence of water in brown dwarfs and EGPs results in fluxes enhanced at just the wavelengths that are optimal for detection on the surface of Earth. This fact made possible the discovery of Gliese 229B (*2*), which helped to inaugurate the field.



Signature of a cool star. Near-infrared spectra of representative methane dwarfs recently discovered by Oppenheimer *et al.* (*15*) (**top**) and by the Sloan Digital Sky Survey (*4, 16*) (**middle** and **bottom** spectra, respectively) [spectra kindly provided by S. Leggett (Hawaii)].

Distinguishing planets and brown dwarfs on the basis of their origin and formation seems sensible. Planets are born in protostellar or protoplanetary disks around stars, whereas brown dwarfs are born directly by the same processes that birth larger stars. Unless a substellar object is solitary, however, we cannot yet identify its origin; a cool object's present does not obviously reveal its past. Secondary characteristics such as element abundance ratios or rotation that might reveal the pedigree of a substellar object have not yet been identified; mass, composition, and age are all that seem necessary to explain its radius, spectrum, and luminosity. Moreover, we do not yet know the mass distributions for the two populations; they may overlap. The current assumption is that the more massive substellar objects are brown dwarfs and that they constitute a smooth extrapolation of the stellar distribution, but theory and data are not yet adequate to justify this speculation. Therefore, we do not know which objects in the bestiary of new exotics with companions are planets and which are brown dwarfs. Although a brown dwarf is not massive enough to ignite stable light hydrogen burning, the more massive brown dwarfs (~0.065 $M_{\odot}$) can temporarily derive some heat from such fusion (although not enough to compensate for their surface loses) and can burn their lithium isotopes. Also, any hydrogen-rich object more massive than ~13 M_J (or ~0.013 $M_{\odot}$) can in its first 10^6 to 10^7 years burn its stores of deuterium. Hence, a planet more massive than ~13 M_J could have a thermonuclear phase and a brown dwarf less massive than ~13 M_J might not. Trying to classify an object on the basis of its thermonuclear potential may thus be flawed.

Current technology does not yet allow direct detection of planets that are in close proximity to, and under the glare of, their parents. Radial velocity studies of nearby stars thus remain important. However, coronagraphic, adaptive optics, and interferometric techniques with high effective angular resolution should soon be able to detect many such planets and planetary systems directly. Direct detection with the Large Binocular Telescope (LBT) (*11*), the Keck interferometer (*12*), and the Terrestrial Planet Finder (*13*), planned for the second decade of the next millennium, is essential for the complete characterization and understanding of this new class of objects.

Within the next few years, the 2MASS (*3*), DENIS (*14*), and Sloan (*4*) surveys alone should capture about a thousand L dwarfs and brown dwarfs. These surveys, along with transit/eclipse and microlensing studies, radial velocity studies, surveys of young star clusters, and spectroscopic follow-up studies with the world's expanding array of 8-m class telescopes, cannot but continue the explosive growth of this exciting new field. Spanning a factor of ~1000 in age, ~100 in mass, and ~20 in T_{eff}, brown dwarfs and EGPs link the planets with the stars. Their study promises to become the next great frontier of both astronomy and planetary science.

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