$3\ R_\oplus$. So around Sun-like stars, small, mostly rocky planets typically predominate over gas giants like Jupiter and Saturn (roughly $10\ R_\oplus$) and gas middleweights like Neptune and Uranus ($4\ R_\oplus$). Our solar system, with its equal numbers of gassy and rocky planets, turns out to be atypical.

That result favors the core-accretion scenario of planet formation, disputed by some, which asserts that accretion of a rocky core precedes the accumulation of a gas envelope from the star's protoplanetary disk. But theorist Alan Boss (Carnegie Institution of Washington) points out that the disk-instability model he has proposed for the rather abrupt formation of gas giants "operates only at greater orbital distances than *Kepler* has been able to sample."

Figure 2b shows the planetary-occurrence distribution in orbital period P. Its principal message—borne out by more detailed representations of the data—is that beyond about 20 days, the distribution is roughly constant in equal intervals of log P. And it's rather insensitive to planet size.

The approximate logarithmic constancy in P implies the same constancy in F_p. The team has exploited the latter to augment its very meager sample of Earth-size planets with F_p less than $F_\oplus$ by means of "a modest extrapolation" from somewhat higher fluxes. That extrapolation yields the conclusion, widely noted in the media, that 22 ± 8% of Sun-like stars have at least one planet of size 1–2 $R_\oplus$ in the habitable zone of stellar fluxes from 0.25 $F_\oplus$ to 4 $F_\oplus$.

That striking conclusion means that there must be Earth-size planets in relatively comfortable orbits around Sun-like stars within a few dozen light-years of the solar system—unless our local neighborhood is very atypical. Such stars, visible to the naked eye, should be amenable to planetary imaging and atmospheric spectroscopy with modest instruments. Some of those planets might then be promoted from "Earth-size" to "Earth-like."

There's no reason to assume that habitable Earth-like planets are exclusive to Sun-like (GK-type) stars. Courtney Dressing and David Charbonneau at Harvard University recently reported the results of their search of the *Kepler*-field data for Earth-size planets orbiting M dwarfs—stars smaller and cooler than the GK stars.[2] Small planets are easier to see in transits across M dwarfs, because they occult larger fractions of the smaller stellar disks. Dressing and Charbonneau estimate that about 15% of M dwarfs have Earth-size planets in their habitable zones.

Kepler impaired

The estimates by the two teams are unlikely to be improved upon in the next few years. "*Kepler* has revealed far more exoplanets than all the other instruments put together," says Marcy, himself a pioneer of the Doppler-oscillation technique that revealed most of the early exoplanets (see the article by Jonathan Lunine, Bruce Macintosh, and Stanton Peale in PHYSICS TODAY, May 2009, page 46). But the failure of one of the orbiter's gyroscopic motors last May—the second such loss—has deprived it of the exquisite pointing stability necessary for continued monitoring of the *Kepler* field.

The orbiter is now scheduled for less demanding tasks. But those cannot provide the anticipated four more years of *Kepler*-field surveillance that would have significantly sharpened the abundance estimates—especially for planets with longer orbital periods.

Bertram Schwarzschild

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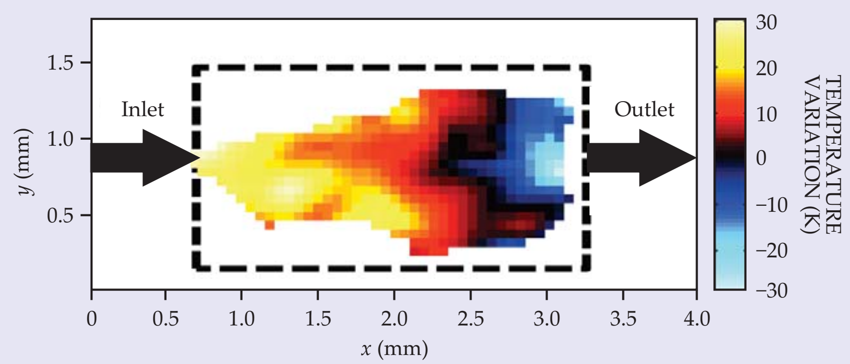
Nuclear magnetic resonance takes a reaction's temperature

A new technique exploits the inverse relation between temperature and the linewidth of a proton resonance.

Industrial catalysis is typically done by flowing gaseous or liquid reactants over a solid catalyst. Because the catalyst is often packed into a chamber in the form of wire mesh, microscopic particles, or some other structured solid with a high surface-to-volume ratio, such reactions tend to be extremely complex—full of hot and cold spots that can affect conversion efficiency. So engineers strive to probe the thermodynamics of the reactions *in situ* to better model their kinetics and optimize reactor design.

In large systems, a few well-placed thermocouples might suffice. But in laboratory-scale systems, such as microreactors or lab-on-a-chip devices, it's often impossible to probe the temperature without disrupting the flow and thereby the reaction itself.

Optical techniques, though noninvasive, don't work when the reactants or the chamber enclosing them are opaque. Nuclear magnetic resonance thermometry is similarly noninvasive but often requires contrast agents that may interfere with a reaction. Traditional approaches using NMR can also lose accuracy in complicated environments. The weak dependence of the resonance frequency of water protons on temperature (3 Hz/K) has made it a widely used thermometer for decades in cases where linewidths in NMR spectra are sharp and the shifts in frequency unambiguous. But place a mouse, for instance, in an NMR magnet and the combination of blood flow, heat, and susceptibility gradients in its tissues produces local variations in the magnetic field that broaden the lines and may mask the small temperature-



A thermal map of gases in the catalyzed conversion of propylene into propane. The inflowing gas and the reactor were held at about 418 K, and the variations about that temperature were extracted from differences in the linewidth of a hydrogen nuclear magnetic resonance signal in different parts of the reactor.

revealing shifts in proton frequency. A catalyst-packed reactor can exhibit the same kind of variations in the field.

This past year UCLA's Louis Bouchard realized that the linewidth itself could serve as a thermometer in gas-phase NMR. He and his colleagues have now developed a thermal mapping technique that exploits the motional averaging experienced by gases at different temperatures when a weak but uniform magnetic field gradient is applied across the reaction.[1]

Once the reaction chamber is placed in the NMR magnet, the researchers apply a broadband RF pulse to tip the spins of hydrogen nuclei and then apply the gradient, during which they record the signal as the spins precess and lose coherence. Relatively cold molecules diffuse little in a given time, so their spins in different regions of the reactor feel different fields and precess with a range of resonant frequencies; the result is a broad NMR line. Warmer molecules, which cover more ground and sample the spatially varying magnetic field more broadly, have a smaller spread in resonant frequencies and hence a narrower collective linewidth.

It's no surprise that when random molecular motion causes nuclear spins to experience more averaging, the NMR signal remains coherent longer and its peaks narrow. Nicolaas Bloembergen, Edward Purcell, and Robert Pound described such effects as early as 1948. But the UCLA group's use of an external gradient for thermometry is new.

From principle to practice

The stronger the magnetic gradient, the more sensitive the linewidth's temperature dependence, a feature that makes the new thermometer tunable. But Bouchard and company discovered that even a gradient as small as 1 mT/m is enough to overwhelm, by roughly an order of magnitude, any residual contribution to a signal's linewidth from susceptibility gradients or other inhomogeneities inside a reaction chamber filled with catalytic metal nanoparticles. That's fortunate, since so small a gradient does not usually interfere with the chemical shifts in NMR peaks that occur during the progression of a reaction as hydrogen-bonding configurations change.

To spatially resolve the temperatures, the researchers turned to standard phase-encoding schemes from magnetic resonance imaging (see PHYSICS TODAY, December 2003, page 24). Those techniques enabled them to map the linewidth-based temperatures into a three-dimensional matrix of voxels whose size sets the resolution. As proof of principle, they measured the thermal variations during the reaction of molecular hydrogen and propylene gas flowing through a small glass tube packed with platinum or palladium nanoparticles. The 2D map shown in the figure—which plots the extracted temperatures averaged over the third dimension and was made from a trial using platinum catalysts—was accurate to within 4% of the absolute temperature and had a spatial resolution of about 100 μm × 100 μm in plane.

The naturally low spin density of gas presents a challenge when the size of a voxel is reduced to submillimeter volumes. Even at room temperature, only about one spin in 10^5 aligns with a 10 T field because the energy difference between spin-up and spin-down hydrogen protons is a tiny fraction of the thermal energy. When temperatures get higher, as they often do in catalytic reactions, the vast majority of spins cancel each other out and the NMR signal from the small net magnetization can be faint.

To obtain the high spatial resolution,

the researchers enriched their reactant gas mixture with parahydrogen, the singlet-state spin isomer of molecular hydrogen. The enhanced magnetization boosted the NMR signal by some four orders of magnitude and reduced the integration times needed to obtain good signal-to-noise ratios.[2] The map shown in the figure took just 30 minutes to make.

Curiously, the presence of precious metal in the chamber doesn't appear to attenuate the RF field because the metal, dispersed as nanoparticles, is far smaller than the skin depth at 400 MHz. "Engineers suddenly have a method for peering inside a working engine—particularly one enclosed by ceramic. A thick metal block is likely to remain impenetrable by the RF field, but if the field frequency is low enough [below 10 kHz or so], the new method should work even through a thin metal shell," says RWTH Aachen University chemist Bernhard Blümich.

The UCLA team plans to take the method far beyond temperature maps. Temperatures come from linewidths, but each voxel measurement also contains the spectroscopic fingerprints of the reaction's chemistry in the frequencies and amplitudes of the NMR peaks. Engineers might be interested in the amount of reactant consumed at different times and temperatures or its conversion rate at, for instance, different points in space, explains Bouchard. "Scientists who study catalytic reactions want their full thermodynamics: spatially resolved chemical potentials, pressure, temperature, the flow of energy . . . everything in one experiment."

Mark Wilson

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Explaining our two-faced Moon

New computer simulations of asteroid impacts on the Moon reveal why the basins on its near side are almost twice as wide as those on its far side.

When the far side of the Moon was first photographed by the Soviet probe *Luna 3* in 1959, its visage was immediately puzzling: Although heavily cratered, the far side lacked the dark, vast lava flood plains visible on the near side, and its impact basins—craters so huge they develop complex morphologies—appeared smaller and less numerous than those on the near side.

With the absence of weather and plate tectonics, the Moon's craters preserve a record of the early solar system—in particular a time roughly 4 billion years ago during the so-called late heavy bombardment when the Moon received most of its scars. Since the 1970s scientists have used that record, together with isotopic analyses of Moon rocks, to date the surfaces of other rocky planets.

But understanding how the basins formed and what accounts for their asymmetry on the near and far sides has been hampered by the lack of consensus on the largest basins' sizes. Most are filled with lava, have ill-shaped rims from the inward collapse of crust, or contain multiple concentric rings—the frozen remnants of the enormous shock wave on impact. Such features frustrate attempts to quantify the width of the original basins.

In 2012 the GRAIL (Gravity Recovery and Interior Laboratory) mission got around those obstacles. For nine months two spacecraft, *Ebb* and *Flow*, flew in tandem in a shallow lunar orbit that eventually passed over the entire surface. As the Moon's gravitational pull on the two spacecraft varied from changes in terrain, so did their rate of separation, measurable to within tens of nanometers per second. The mission allowed the GRAIL team to map the gravity field in fine detail.

Mark Wieczorek (Paris Institute of Earth Physics) and colleagues removed the effects of topography from the data and used the residual field to map the thickness of the crust.[1] The ejection of material from an asteroid impact is so great that it and the subsequent uplifting of the underlying mantle from the release of pressure dramatically thin the crust. So the researchers' map of thickness variations, shown in the figure, unmasked the hidden craters and unambiguously determined their sizes.

Wieczorek and his postdoc Katarina Miljković were struck by the stark