

Such high relative velocities are not uncommon in the solar system. Indeed, the object that struck Earth to form the Moon had a relative velocity of that magnitude.

Rare and common

The hot grains of tektite and obsidian that show up in HD 172555's IR spectrum are small enough that the star's radiation pressure would drive them away from their current 6-AU orbit within 0.1 million years. The SiO molecules would likely condense and reform minerals on the same time scale. Given that rocky planets take 100 My to form, catching a giant impact in HD172555, despite its being an ideal setting, seems fortunate, though not wildly improbable.

The odds of catching other giant impacts would be higher if one could detect not just the ground-up, kicked-out debris but also the hot glowing surface of the impacted planet. As Michael Meyer of ETH Zürich and his collaborators pointed out in a recent paper, a single stellar system could experience several impacts as its rocky planets form.² If a system has two Earth-sized planets, each might have suffered two collisions with Mars-sized objects to reach its final mass. The impacted surfaces could glow for 2 My, so the chance of spotting one glowing surface during the 100 My of rocky planet formation would be roughly 1 in 10. Not bad.

Surprisingly, thanks to its bigger combined area, the ground-up dust from a Pluto-sized impactor is far brighter than the hot glowing surface of an Earth-sized impactee. The next gen-

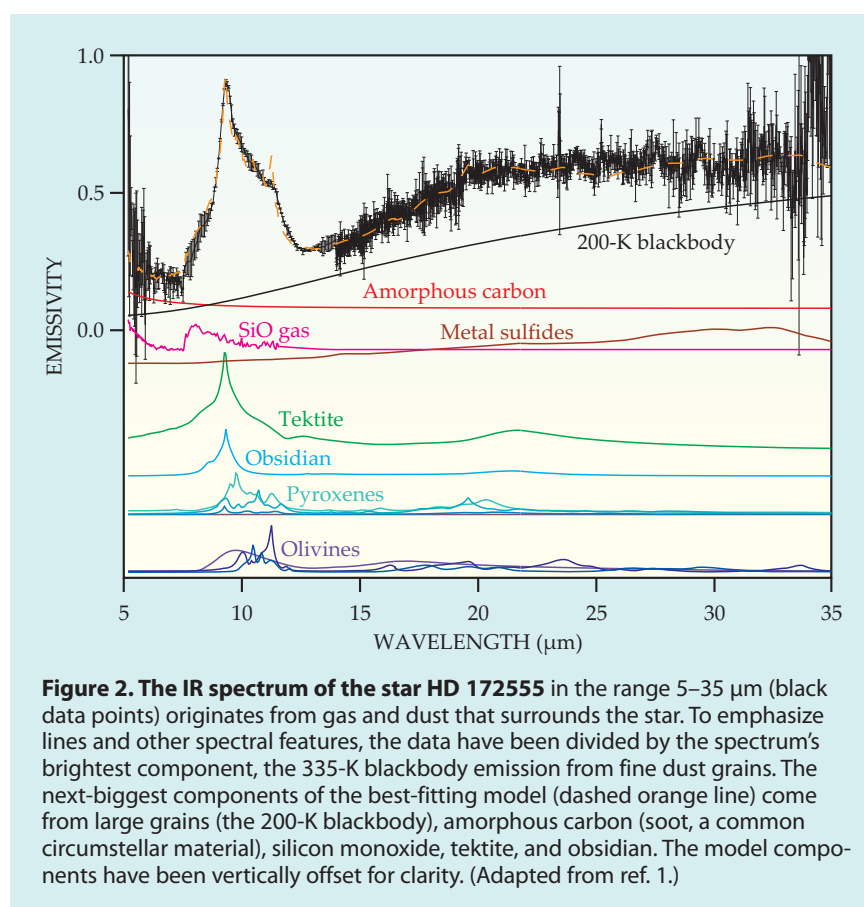


Figure 2. The IR spectrum of the star HD 172555 in the range 5–35 μm (black data points) originates from gas and dust that surrounds the star. To emphasize lines and other spectral features, the data have been divided by the spectrum's brightest component, the 335-K blackbody emission from fine dust grains. The next-biggest components of the best-fitting model (dashed orange line) come from large grains (the 200-K blackbody), amorphous carbon (soot, a common circumstellar material), silicon monoxide, tektite, and obsidian. The model components have been vertically offset for clarity. (Adapted from ref. 1.)

eration of giant ground-based telescopes will be needed to spot those surfaces. Still, the evidence of one impact outside our solar system suggests that other Earth-like planets do lie within a detectable range.

Charles Day

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Superhydrophobic surfaces reduce drag

Microscopic features on a wall can have an enormous influence on macroscopic flows along it.

Turbulent flows of a liquid along a wall experience frictional drag, a macroscopic phenomenon that strongly affects the efficiency, costs, and other parameters of countless engineering systems—from marine vessels to oil pipelines. The drag arises from shear stress, the rate per unit area of momentum transfer from the flow to the wall. To reduce the shear stress, engineers could add polymers to the flow, inject bubbles against the surface, or combine the two methods. But those approaches bear their own costs.

Researchers led by Jonathan Rothstein at the University of Massachusetts Amherst now offer a proof-of-principle demonstration of a new, passive option for reducing drag in a turbulent flow.¹ They tailored the microscale structure

of a hydrophobic material—polydimethylsiloxane (PDMS), akin to the rubbery polymer used to caulk bathtubs—to create air pockets that allow the flow to “slip” (shear free) at the liquid–air interface. The greater the area covered by air pockets, the greater the overall reduction in shear stress—up to 50%, the researchers estimate, judging from particle-image velocimetry and pressure-drop experiments over a wide range of Reynolds numbers.

The physics behind the effect goes back nearly two centuries. Since the 1820s, evidence began mounting that fluids come to a virtual standstill at a solid surface, at least macroscopically. In 1904 Ludwig Prandtl interpreted that no-slip condition as an effect of friction, which causes layers of fluid immedi-

ately adjacent to a wall to stick to its surface. Frictional effects, he argued, were thus experienced in a thin boundary layer near the wall. Outside that boundary layer, the flow was essentially inviscid, and friction could be considered negligible (see the article by John D. Anderson Jr in *PHYSICS TODAY*, December 2005, page 42).

A century of experiments have borne out Prandtl's theory. Viscous effects in the turbulent regime, it turns out, are mostly restricted to a thin region inside the boundary layer, known as the viscous sublayer. And velocity gradients normal to the surface—the source of the shear stress—can indeed be enormous over very short distances. For hydrophobic surfaces, the approach to reducing drag thus boils down to reducing

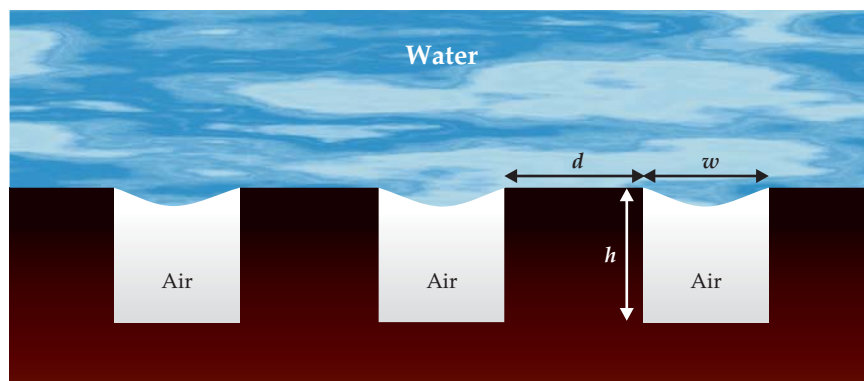


Figure 1. A periodic array of microscopic ridges or grooves in a hydrophobic surface creates a heterogeneous interface, part liquid–solid and part liquid–air, when a column of water flows over the top (and into the page). University of Massachusetts Amherst researchers considered two geometries: one in which the width w of each pocket and the spacing d between them is $30\text{ }\mu\text{m}$, and one in which w and d are both $60\text{ }\mu\text{m}$ (the height h is $25\text{ }\mu\text{m}$ in both cases). Both geometries contain a 50% shear-free interface. (Adapted from ref. 1.)

the liquid–solid contact area that generates it. Because the viscosity of air is far smaller than that of water, it moves easily and the liquid–air interface maintains a slip velocity close to that of the bulk fluid.

The rough and the smooth

Rough surfaces are far more common in nature (and on ships' hulls) than smooth ones. Fortunately, the combination of roughness and hydrophobicity—the property that prompts water to bead up into a near-spherical ball on a lotus leaf, for instance—also lowers the free energy of an air–water interface such that surface tension can support the liquid layer between neighboring peaks.

To systematically investigate the drag reduction conferred by such superhydrophobic surfaces—that is, ones both rough and hydrophobic—in both laminar and turbulent flow regimes, the UMass team lithographically produced a 1-m-long surface having corrugated ridges in their PDMS (see figure 1). They then fashioned a 15-mm-deep flow channel—a rectangular pipe whose bottom held the corrugated PDMS surface and whose top was made from smooth, transparent acrylic. To monitor the fluid's velocities throughout the channel and to within $50\text{ }\mu\text{m}$ of its surface, they seeded the flow with neutrally buoyant silvered glass spheres, illuminated a plane of the channel using laser light, and captured the motion on video camera.

Figure 2 illustrates the dramatic drop in the coefficient of friction C_f deduced from those particle-image velocimetry measurements and from separately run pressure-drop measure-

ments along a channel. In the turbulent regime—at Reynolds numbers above 2100 in this case—frictional drag was observed to dramatically decrease as smooth surfaces were swapped for superhydrophobic ones. Indeed, the critical Reynolds number at which the onset of drag reduction occurs is related to the ratio of two length scales—one associated with the geometry of the surface corrugations, the other with the thickness of the viscous sublayer.

The Reynolds number is a dimensionless number frequently interpreted as the ratio of inertial to viscous terms in the Navier–Stokes equations. At low Reynolds numbers, viscous forces dominate throughout the channel and the flow is silky smooth, or laminar. It's no surprise, then, that for laminar flow, the drag-reducing effect of microscopic ridges under a macroscopically deep (15-mm) channel is minimal—about 1%, the researchers estimate. That's not to say drag can't be reduced in laminar flows by the use of superhydrophobic walls. It can, and by an equally dramatic amount, but only in the context of microfluidics, in which the size of the corrugations is on the same order as the channel depth.²

At the high Reynolds numbers characteristic of the turbulent regime, inertial forces dominate. Indeed, they pervade the entire channel except for the thin viscous sublayer closest to the wall. That sublayer, just $100\text{ }\mu\text{m}$ thick in the UMass system, becomes thinner (to about $50\text{ }\mu\text{m}$) as the Reynolds number increases and is the only part of the channel that transfers momentum to the wall.

The efficient mixing of fluid layers and greater shear stress are responsible



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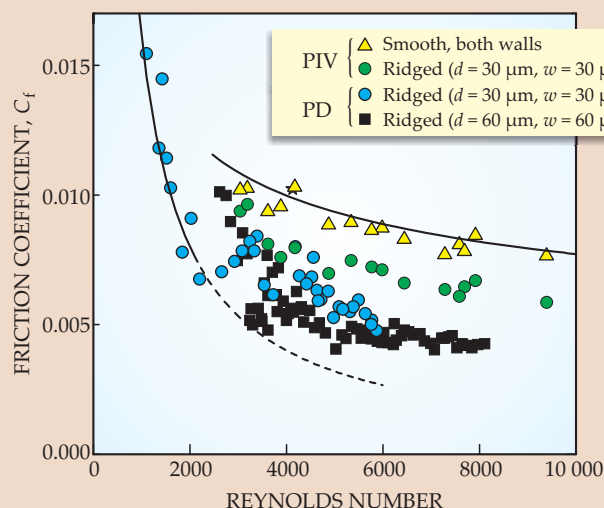


Figure 2. The coefficient of friction C_f refers to the shear stress at a wall divided by the kinetic energy density of the flow and is plotted here for various surfaces as a function of Reynolds number. Solid lines indicate

the predicted C_f along a smooth channel when the flow is laminar (the leftmost curve) and when it becomes turbulent (top-most curve). Data sets are distinguished by whether they are calculated from particle-velocimetry measurements (PIV) or from pressure drops (PD) observed along the channel. The onset of drag reduction occurs in the turbulent regime where the height of the viscous sublayer (about 50 μm) is on the scale of the surface corrugations. Moreover, their effect becomes increasingly pronounced as their width and spacing increase and as both walls (top and bottom) of a rectangular flow channel are made hydrophobic. (Adapted from ref. 1.)

for the jump in the friction coefficient as the flow changes from smooth to turbulent and for the emergence of a veritable zoo of coherent structures such as the ones shown on this month's cover. The tangles and swirling eddies are thought to form in the boundary layer and slowly percolate into the bulk fluid.

Rothstein's UMass colleague Blair Perot and graduate student Michael Martell found those structures in numerical simulations of the fluid's path and velocity in flow channels modeled on the experiments (though with flow-channel depth an order of magnitude smaller).³ Their calculations complement the experimental results. The velocity of water is constrained to be zero at the top of each ridge, but finite slip velocities emerge from the Navier-Stokes equations along the air-water in-

terface. The topology of the surface, the simulations suggest, affects not just the drag reduction—with increased spacing between ridges producing greater slip velocities—but also the location of the turbulent eddies, the mean shear, and the energy dissipation.

Toward practical systems

Should we expect to see superhydrophobic surfaces grace the hulls of ships anytime soon? Research is far from addressing practicalities: The UMass experiments explored flow speeds under 1.5 m/s (3 knots), at pressures under 5 kPa (0.5 m of water), and at Reynolds numbers under 10 000. Supertankers have Reynolds numbers in the tens of millions, but with viscous-sublayer thicknesses comparable to those in the UMass experiments.

Nevertheless, Rothstein is optimistic. "In 1987, 3M coated an America's Cup yacht with a plastic film embedded with riblets," minute, v-shaped grooves that also reduce drag passively, albeit in an extremely narrow band of Reynolds numbers. It won. "And, at least in principle," says Rothstein, "hydrophobic ridges could be produced with even finer features to prevent the air pockets from wetting under several meters of water." The US Navy, which funds the research, remains interested.

Mark Wilson

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physics update

These items, with supplementary material, first appeared at <http://www.physicstoday.org>.

A new exoplanet to test tide theories. Almost 400 extrasolar planets have been found to date (see *PHYSICS TODAY*, May 2009, page 46), but a new planet reported by Coel Hellier (Keele University) and colleagues stands out. Like many exoplanets, theirs, dubbed WASP-18b, is massive (10 times the mass of Jupiter) and has a small orbital radius (only 1/50th of Earth's). But its orbital period of only 0.94 day is the shortest for any "hot Jupiter" yet observed. Moreover, its large mass and small orbit are predicted to cause the strongest tidal interactions of any known star-planet system. According to current theory, the tidal bulge that the planet raises on its host star exerts a torque that will drain angular momentum from the planet and cause it to spiral inward. (For more on tidal interactions, see *PHYSICS TODAY*, August 2009, page 11.) If the star's tidal dissipation rate is comparable to what's been measured for binary stars and for the gas giants in our own solar system, the infall will be quick: WASP-18b has less than a million

years left in a lifetime, estimated from the age of its host star, of about a billion years. Over the next decade, WASP-18b's death spiral should produce a measurable shift in the planet's observed transit time. The absence of tidal decay—a notable possibility, given the rarity of finding a planet so close to the end of its life—would constitute direct evidence for a different class of tidal interactions in the host star and provide new constraints on models of stellar interiors. (C. Hellier et al., *Nature* **460**, 1098, 2009.) —RJF

Bright-eyed polymer. Light sensors—photodetectors—have myriad uses in scientific, industrial, and consumer settings: Digital cameras, environmental monitors, remote controls, surveillance equipment, and biosensors are just a few applications. Most photodetectors are made from inorganic semiconductors and are sensitive in some limited waveband in the range between IR and UV. A new photodetector, however, that uses a semiconducting polymer shows good responsiveness from UV (300 nm) to near-IR (1450 nm), as shown in the figure. The polymer is a small-bandgap semiconductor that exhibits photoinduced, ultrafast electron transfer to fullerenes—blended with the polymer in the form of PC₆₀BM. Sandwiched between two