

apparent change in angular direction to a distant object as Earth orbits the Sun during a year as a fundamental distance scale (9). Gaia precision is an improvement on the best astrometry currently available by some 3 orders of magnitude, while its sensitivity provides an improvement of 4 orders of magnitude. One of Gaia's prime subjects will be galaxy evolution, including measuring the distribution of dark matter on whatever scales it is found. The technically most difficult aspect of dark matter studies in astrophysics is precision mass measurement. Usually having access only to line-of-sight velocity data and knowing little of transverse velocities means that only partial information can be modeled. Gaia will provide precision transverse kinematic data, thus giving access to reliable six-dimensional phase space measures of location and speed for large

numbers of objects, a critical precondition for accurate mass and orbit determinations.

Dark matter is the dominant gravitating mass in the Universe. It is perhaps a mix of several ingredients, with different contributions dominant on different scales, from the extremely small scale of weakly interacting massive particles to the very long scales of massive neutrinos. Disentangling this mix requires quantitative determination of the three-dimensional distribution of mass in dark matter-dominated systems on astrophysical scales to complement direct detection and creation experiments on Earth. As galaxies have been evolving for 13 billion years in real dark matter halos since they became gravitationally bound, quantification of the relevant astrophysics is also necessary. Despite the challenges, real progress is being made, while dra-

matic advances are anticipated, with the combination of the LHC and Gaia.

References and Notes

1. V. Springel, C. S. Frenck, S. D. M. White, *Nature* **440**, 1137 (2006).
2. V. Belokurov *et al.*, *Astrophys. J.* **654**, 897 (2007).
3. G. Gilmore *et al.*, *Astrophys. J.* **663**, 948 (2007).
4. M. Walker *et al.*, *Astrophys. J.* **667**, L53 (2007).
5. G. Gilmore, R. F. G. Wyse, K. Kuijken, *Annu. Rev. Astron. Astrophys.* **27**, 555 (1989).
6. S. Majewski, *Annu. Rev. Astron. Astrophys.* **31**, 575 (1993).
7. K. Freeman, J. Bland-Hawthorn, *Annu. Rev. Astron. Astrophys.* **40**, 487 (2002).
8. European Space Agency, Research and Scientific Support Department, www.rssd.esa.int/Gaia
9. Parallax distances are so fundamental in astronomy that the basic distance unit is the parsec (pc), the distance of an object that displays a parallax of one second of arc. $1 \text{ pc} = 3.26 \text{ light-years} = 3.10^{16} \text{ m}$.

10.1126/science.1165790

CHEMISTRY

A Curious Antipathy for Water

Steve Granick and Sung Chul Bae

Imagine that you are a water molecule at a hydrophobic (water-repellent) surface. Given the chance, you would bead up with other water molecules to form a droplet, just as water beads up on raincoats or leaves of plants (see the figure, left panel). But what would you do if you were inside a droplet, yet located very near the hydrophobic surface? Water molecules in this situation cannot leave the surface although they would if they could; they are frustrated. Such proximity of water to a hydrophobic surface is fundamental to the so-called hydrophobic effect. Its reasons are disputed, as is its definition.

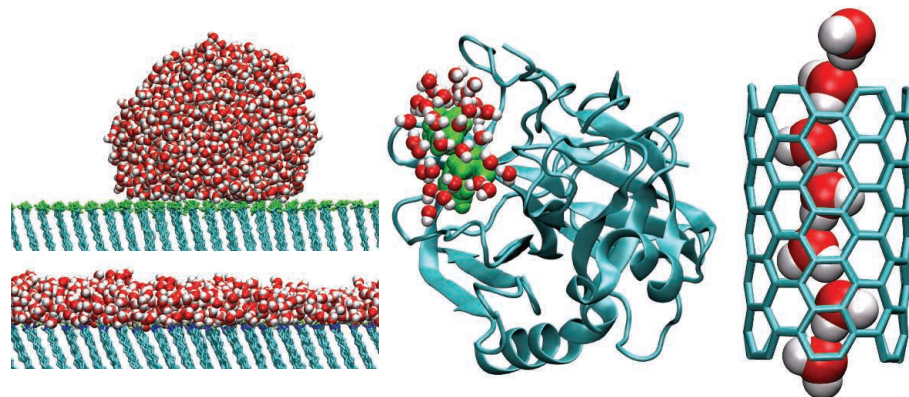
Not in dispute is its importance. For example, the side chains of roughly half the amino acids are polar, while those of the other half are hydrophobic; the nonmixing of the two is key to steering the folding of proteins and other self-assembly processes (see the figure, middle panel). As a second example, the fact that oil and water hardly mix is at the root of the self-assembly of supramolecular structures known as cell membranes (in biology) and micelles (in technology), where the self-assembling molecules contain both nonpolar and polar moieties. Furthermore, when the gap between two hydrophobic surfaces becomes critically small, water is

ejected spontaneously, whereas water films confined between symmetric hydrophilic surfaces are stable (1).

Hydrophobicity shows up differently in carbon nanotubes, within which a hydrogen-bonded chain of water molecules can form, stretching like a thread down the middle of the nanotube (see the figure, right panel) (2). The unusual hydrogen-bonding geometry and nonstick surface result in flow essentially

How does water meet a hydrophobic surface? Like great art, everyone recognizes hydrophobicity but few agree on the details.

without friction (3). Such water-filled nanotubes switch from hydrophobic at room temperature to hydrophilic when the temperature is lowered to 8°C (4), in line with predictions that a switch of this kind can happen because the free energy of a full nanotube is very close to that of an empty nanotube (2). The observation opens the possibility that temperature may one day be used as a switch to make carbon nanotubes selectively suck up chemicals



How water meets different hydrophobic elements. (Left) On flat planar self-assembled monolayers, the situation is simplest: The contact angle is high when the monolayer is terminated uniformly with CF_3 groups, and zero when it is terminated uniformly with OH groups. (Middle) The situation is more complex on the surface of a protein, α -chymotrypsin in this example. Hydrophobicity of the amino acid residues is weaker than in the left panel, the size of the hydrophobic patch is smaller, and nothing is planar. For these reasons, the tendency to dewet is less than in the left panel. Water is predicted to envelop even the hydrophobic (green) patch of amino acids, but likely with more fluctuation than at hydrophilic patches (1, 13). (Right) Water fills a carbon nanotube spontaneously, forming linear hydrogen-bonded threads of water running down the middle (2), yet the simultaneous tendency to dewet causes it to flow through the tube essentially without friction (3).

Departments of Materials Science and Engineering, Chemistry, and Physics, University of Illinois, Urbana, IL 61801, USA. E-mail: sgranick@uiuc.edu

like with a straw—not only water, but potentially other solutes also (5). It also confirms the well-known weakening of hydrophobic interactions upon cooling below room temperature (6).

Despite its obvious importance, physical insight into the origins of hydrophobicity is not easy to come by. Thermodynamic measurements are one approach, but interpreting their physical significance is extraordinarily subtle (6). Theoretical considerations and computer simulations show that a key concept is the size of the hydrophobic object (7–9). Water molecules can wrap efficiently around hydrophobic elements with a radius of curvature of 1 nm or less. When water meets hydrophobic surfaces that are flatter than this, it forms a molecularly thin cushion of depleted density between it and the hydrophobic surface.

The fly in the ointment is experiment. Putative depletion layers must fight against attraction of water to any hydrophobic surface, a ubiquitous force known as van der Waals attraction. This is probably why laboratory data have provided evidence both for [(10, 11) and references therein; (12)] and against (13) this phenomenon. Despite that controversy, there is consensus that the expected thickness of a depletion layer is less than the dimension of even one water molecule. This small thickness matters for the following reason: If water meets hydrophobic surfaces softly, because van der Waals attraction outweighs its natural reluctance to do so, the frustrated interface should fluctuate wildly—as people also do, when they are unsure about what decision to make. Experiments (1) and theory (14) support this view, which merits further investigation.

But a caution is worth emphasizing: Hydrophobicity depends on the eye of the beholder. Some of the heated discussion in this field can be traced to the simple fact that people have different ideas in mind. One common definition is that water droplets on a planar hydrophobic surface possess a contact angle larger than 90°; but given that nothing dramatic changes when the contact angle falls below this or any other point, it is just a convenient but arbitrary definition. This has special relevance when seeking to distinguish between polar and hydrophobic patches on the surface contours of proteins. Many cases of modest hydrophobicity are akin to a bald man with a few thousand hairs on his head—he is on the bald side but others are much more bald. To understand better how hydrophobicity acts in the natural and technological worlds, and to overcome controversies, the following questions are worth future investigation. First, how does it matter whether a sur-

face has the same wettability (hydrophobic or hydrophilic) everywhere, or is “patchy” from spot to spot? Answers will bring understanding in this field into closer contact with emerging issues in fields as diverse as protein folding and surface science.

Second, scientists have concentrated on systems that are subject to steady external conditions, such as a low temperature that causes proteins to denature. We do not yet have good ways to think about how aqueous systems respond to an extreme but perhaps transient change of environment. Is it realistic to expect a general theory of hydrophobic surfaces when temperature and pressure change in time and space? Empiricism shows that what matters is not just the instantaneous separation between hydrophobic surfaces but also the time (or frequency) of their contact (1); the timeline of change also matters.

Third: When does water act truly unlike other fluids? Spectroscopic studies of vibrations in water molecules are a technical tour de force but are problematic to interpret (15). Prevalent computational models use point charges and do not explicitly recognize quantum mechanics; it may be worth inquiring more critically into the assumptions made in these models. Moreover, too often the models are specific to the system under study, but common responses strongly suggest more universality. For example, when nanotubes fill with water at low temperature, one

approach is to explain this in terms of the hydrophobic effect (4), but it can also be understood on the basis of more general principles of the competition between enthalpy and entropy (16). The challenge, then, is to predict from theory, rather than from empiricism, what makes water so special.

References and Notes

1. X. Zhang, Y. Zhu, S. Granick, *Science* **295**, 663 (2002).
2. G. Hummer, J. C. Rasaiah, J. P. Noworyta, *Nature* **414**, 188 (2001).
3. A. Kalra, S. Garde, G. Hummer, *Proc. Natl. Acad. Sci. U.S.A.* **100**, 10175 (2003).
4. H.-J. Wang, X.-K. Xi, A. Kleinhammes, Y. Wu, *Science* **322**, 80 (2008).
5. A. Kalra, G. Hummer, S. Garde, *J. Phys. Chem. B* **108**, 544 (2004).
6. D. Ben-Amotz, B. Widom, *J. Phys. Chem. B* **110**, 19839 (2006).
7. F. H. Stillinger, *J. Sol. Chem.* **2**, 141 (1973).
8. K. Lum, D. Chandler, J. D. Weeks, *J. Phys. Chem. B* **103**, 4570 (1999).
9. J. Janecek, R. R. Netz, *Langmuir* **12**, 8417 (2007).
10. A. Poynor *et al.*, *Phys. Rev. Lett.* **97**, 266101 (2006).
11. A. Poynor *et al.*, *Phys. Rev. Lett.* **101**, 039602 (2008).
12. M. Mezger *et al.*, *J. Chem. Phys.* **128**, 244705 (2008).
13. K. Kashimoto *et al.*, *Phys. Rev. Lett.* **101**, 076102 (2008).
14. D. Chandler, *Nature* **437**, 640 (2005).
15. M. Sovago *et al.*, *Phys. Rev. Lett.* **100**, 173901 (2008).
16. L. Maibaum, D. Chandler, *J. Phys. Chem. B* **107**, 1189 (2003).
17. We are grateful for comments from D. Ben-Amotz, D. Chandler, and S. Garde. Supported by the Department of Energy, Basic Energy Sciences, Division of Materials Sciences, DEFG02-02ER46019.

10.1126/science.1167219

ECOLOGY

Crops for a Salinized World

Jelte Rozema¹ and Timothy Flowers²

Cultivation of salt-tolerant crops can help address the threats of irreversible global salinization of fresh water and soils.

Currently, humans use about half of the fresh water readily available to them to support a growing world population [expected to be 9.3 billion by 2050 (1)]. Agriculture has to compete with domestic and industrial uses for this fresh water. Good-quality water is rapidly becoming a limited and expensive resource. However, although only about 1% of the water on Earth is fresh,

there is an equivalent supply of brackish water (1%) and a vast quantity of seawater (98%). It is time to explore the agronomic use of these resources.

Adding to the increasing competition for fresh water is the gradual and irreversible spread of salinization. Salinity is affecting fresh water and soil, particularly in arid and semiarid climatic zones. Ironically, irrigation has resulted in the accumulation of salt to above normal concentrations in the rooting zone of arable land, as high rates of evaporation and transpiration draw soluble salts from deep layers of the soil profile. The water and salt balance has also changed in regions where dryland agriculture—growing crops without

¹Department of Systems Ecology, Vrije Universiteit, Amsterdam, Netherlands. ²School of Life Sciences, John Maynard Smith Building, University of Sussex, Falmer, Brighton BN1 9QG, UK and School of Plant Biology, Faculty of Natural and Agricultural Sciences, The University of Western Australia, Crawley, Western Australia, 6009, Australia. E-mail: jelte.rozema@falw.vu.nl; t.j.flowers@sussex.ac.uk