Brief History of Time: From the Big Bang to Black Holes (1988). Thus, years ago, when I was teaching an introductory course on the history and philosophy of science, I would ask the students whether they had heard of Copernicus, and everyone would raise their hand, but when I asked about Aristarchus of Samos, usually no hands went up. If I were still teaching, in addition to my usual covering of Aristarchus and Copernicus, I would teach about the Kerala school as well, thanks to Deshmukh's book.

Reference

1. T. Heath, *Aristarchus of Samos, the Ancient Copernicus: A History of Greek Astronomy to Aristarchus* [. . .], Clarendon Press (1913; reprint, Dover, 1981), p. 302.

Frank R. Tangherlini
(frtan96@gmail.com)
San Diego, California

Observing interstellar molecular hydrogen

Johanna Miller's Search and Discovery story "Ten billion years ago, galaxies were already running out of gas" (Physics Today, December 2021, page 20) describes evidence that some galaxies deplete their interstellar matter to fuel star formation. Particularly important are cold interstellar gas clouds, where the atomic-to-molecular transition is a key step in sustaining new star formation. The story highlights recent Atacama Large Millimeter/Submillimeter Array observations of molecular gas in carbon monoxide microwave emission and far-IR emission from dust grains.[1] But these two sentences were misleading: "Measuring the galaxies' H_2 content directly isn't an option because H_2 molecules themselves are essentially invisible. They're symmetric and lack electric dipole moments, so they don't absorb or emit radiation when they rotate and vibrate."

Rumors of H_2 invisibility have been greatly exaggerated. Although it's true that the H_2 ground electronic state has no dipole moment, two low-lying electronic states (molecular orbitals from 1*s*–2*s* and 1*s*–2*p*) do have dipole moments. Electronic absorption lines into those states lie in the far-UV and are known as the Lyman and Werner bands.[2] Widely observed in the interstellar medium by the *Copernicus* and *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) satellites, they provide diagnostics of the molecular fraction, gas temperature, and UV radiation field in diffuse and translucent interstellar clouds. *FUSE* also surveyed H_2 in two external galaxies, the Large and Small Magellanic Clouds orbiting the Milky Way.[3]

UV H_2 lines have also been seen in strong quasar absorption systems redshifted into the visible band.[4] For systems in the Milky Way and local galaxies, measuring those absorption lines requires finding a bright UV background source, such as a hot star or quasar, behind the absorbing gas. That makes dark molecular clouds hard to probe in the UV. But *FUSE* observed H_2 in a number of translucent clouds[5] with one to five magnitudes of visual extinction and molecular fractions up to 75%.

Thanks to cosmological redshifting of light, H_2 has now been observed in distant intervening galaxies in spectra of background quasars. The H_2 far-UV absorption lines are shifted into portions of the UV accessible to the *Hubble Space Telescope* for galaxy redshifts $z > 0.05$ (a distance of 680 million light-years). At redshifts $z > 1.8$, the H_2 lines can be observed by optical spectrographs. The European Southern Observatory's Very Large Telescope in Chile has detected H_2 in more than 22 distant galaxies (damped Lyman-alpha absorbers) at redshifts z between 1.96 and 4.22, corresponding to cosmological distances of 10.3 to 12.2 billion light-years. The recent Decadal Survey on Astronomy and Astrophysics supported plans for a 6 m optical, UV, and IR space telescope. With greatly enhanced sensitivity in the far-UV (90–200 nm), that facility would be a powerful tool for probing the atomic and molecular gas that fuels star formation in galaxies.

References

1. K. E. Whitaker et al., *Nature* **597**, 485 (2021).
2. J. M. Shull, S. Beckwith, *Annu. Rev. Astron. Astrophys.* **20**, 163 (1982).
3. B. D. Savage et al., *Astrophys. J.* **216**, 291 (1977); J. M. Shull, C. W. Danforth, K. L. Anderson, *Astrophys. J.* **911**, 55 (2021); J. Tumlinson et al., *Astrophys. J.* **566**, 857 (2002).
4. P. Petitjean, R. Srianand, C. Ledoux, *Astron. Astrophys.* **364**, L26 (2000).
5. B. L. Rachford et al., *Astrophys. J. Suppl. Ser.* **180**, 125 (2009).

J. Michael Shull
(michael.shull@colorado.edu)
University of Colorado Boulder