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Mystery of the Missing Oxygen

by Catherine Nisbett Becker | July 2015

Oxygen seems to be everywhere. It is the third most common element in the universe, behind hydrogen and helium. And molecular oxygen, or O_2, is plentiful on Earth. It makes up about 21 percent of our atmosphere, and we breathe in about 19 cubic feet of O_2 every day. It seems natural that breathable molecular oxygen should suffuse interstellar space, and indeed, astronomers in the 1970s predicted that O_2 would turn out to be the third most common molecule in the universe, behind molecular hydrogen and carbon monoxide. But it didn't. When we look beyond the boundaries of our own atmosphere, O_2 is incredibly rare.

NASA

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In 1998, NASA launched the Submillimeter Wave Astronomy Satellite (SWAS), which in part was designed to detect molecular oxygen. It did not. Astronomers assumed the detector was defective until they aimed it at Earth—and found a lot of O_2. Astronomers have only found two other sites with detectable O_2. The Odin satellite found it in the Rho Ophiuchi cloud, a stellar nursery, in the early 2000s. In 2010, the European Herschel Space Observatory found O_2 in the Orion Nebula. In both places the observed concentration of O_2 was far below theoretical predictions. Where is all the missing O_2? [See New Asteroid Belt, Orion Nebula, Provide Clues to Planet Formation, July 2001.]

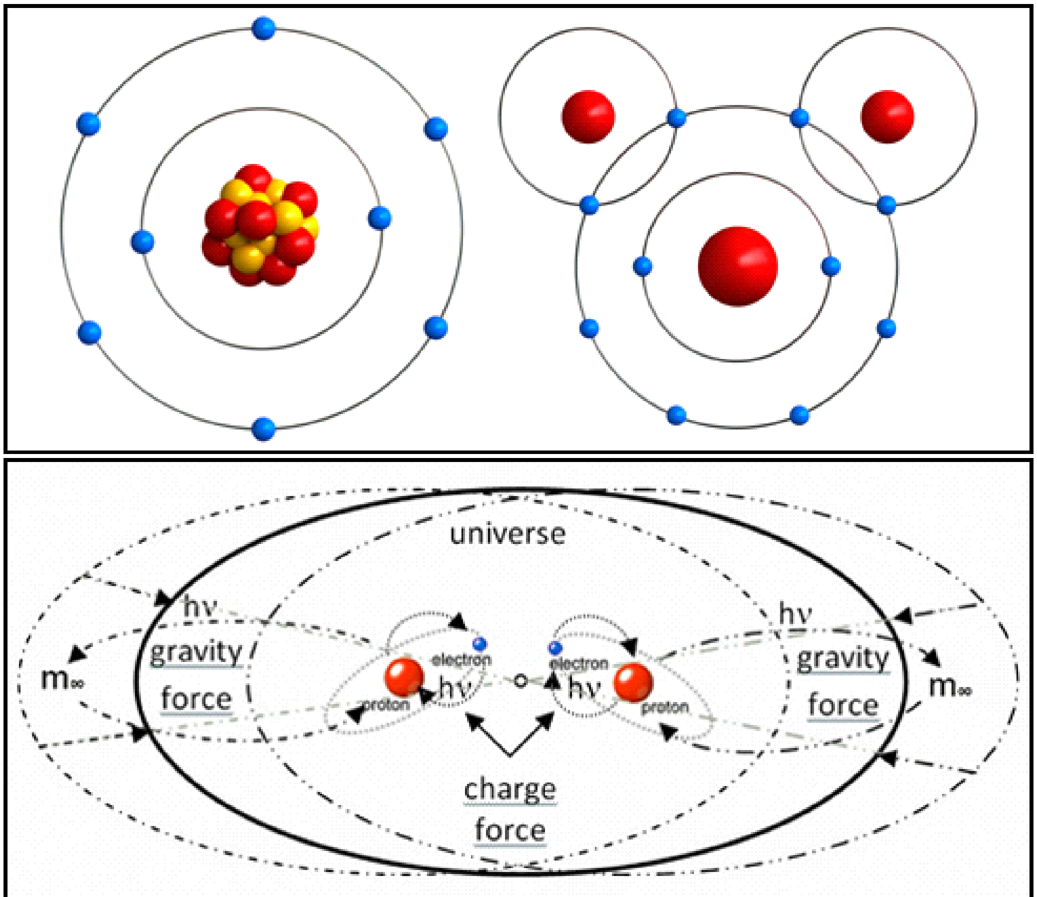
ESA

In 2010, the European Herschel Space Observatory found O_2 in the Orion Nebula. However, the observed concentration of O_2 was far below theoretical predictions.

Recently, Jiao He, Gianfranco Vidali and colleagues from Syracuse University in New York and San José State University in California took to the laboratory to find out. They wanted to study the binding energy of oxygen in two common interstellar compounds: water ice and silicate. They let oxygen bond to both compounds in order to discover how much energy was necessary to break those bonds and shake the oxygen loose. They found that more than twice as much energy was required than had been previously thought. The group published their results in the March 10, 2015 issue of the *Astrophysical Journal*.

Oxygen and Binding Energy

Oxygen atoms are originally formed by fusion in the dense cores of massive stars. An atom of oxygen is extremely reactive. In the atom's outermost energy level, or valence band, there are two holes, or spaces for electrons. Atoms naturally seek to fill their valence bands, either by giving up extra electrons, as in the case of hydrogen, or by taking electrons from other atoms. Water, H_2O, is such a stable compound because the two electrons from the two hydrogen atoms fill the two holes in the oxygen atom's valence band. Oxygen does not just bond to hydrogen; it will form compounds with nearly every other element on the periodic table. On Earth, when metals are left exposed, they often oxidize. And oxygen also binds to itself, forming breathable O_2.



Top: Shutterstock; Bottom: Steve Agnew

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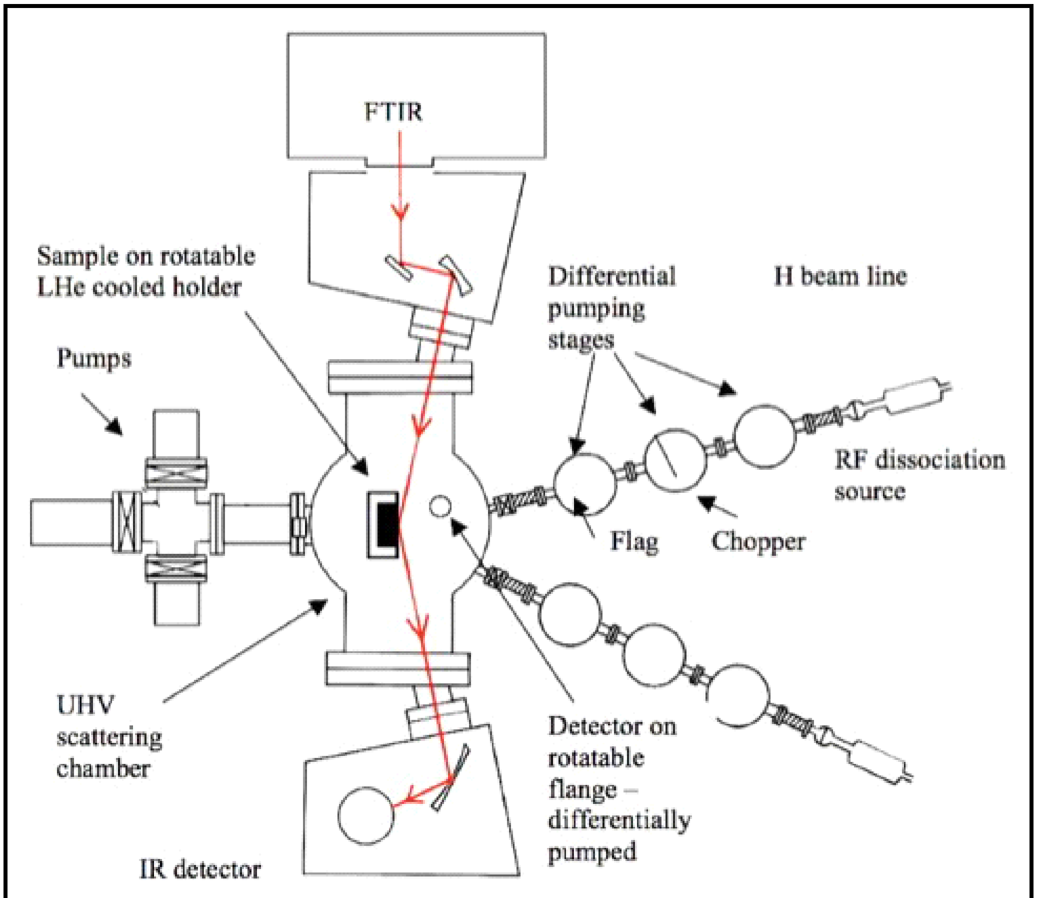
Things that are together tend to stay together. If you want to cut up an apple or rip a piece of paper in half, you have to add kinetic energy (the energy of an object in motion) to move different parts of the object in different directions. In order to free electrons from atoms, you must add electromagnetic energy to jump the electron to such a high energy level that it is no longer attached to the nucleus. Even producing nuclear energy from fission, a process of breaking apart an atomic nucleus, initially requires an input of energy to get the reaction going. The energy you must add in order to disassemble a whole into parts is called "binding energy," and measuring it is important throughout physics and astronomy.

The Experiment

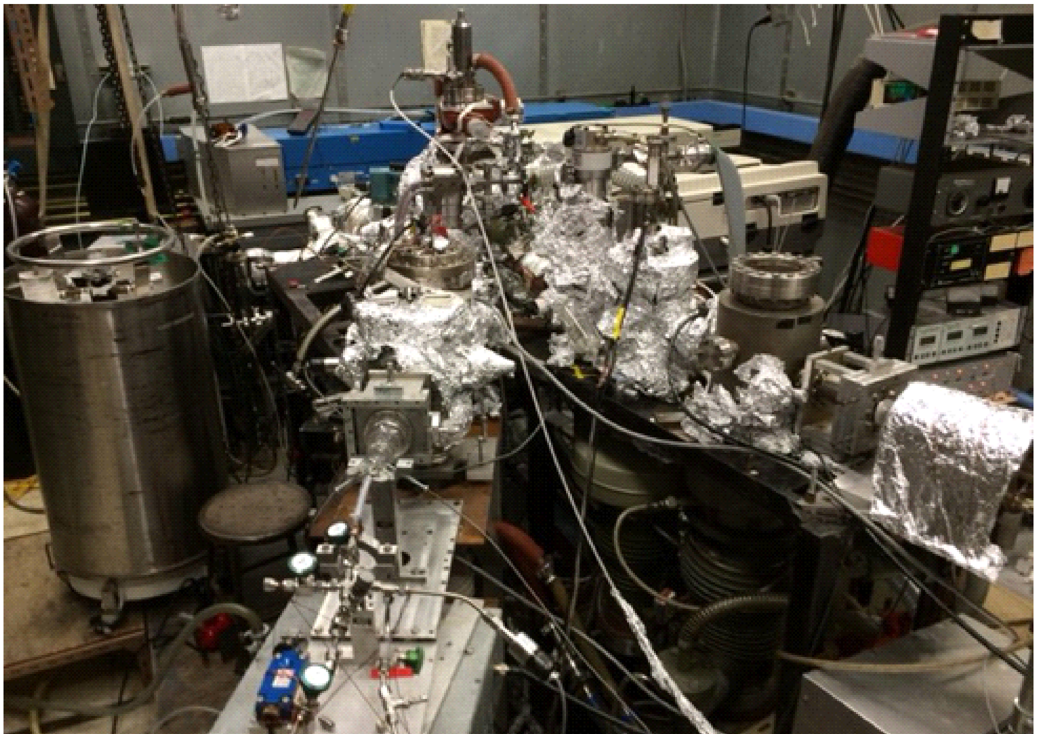
Jiao He and his colleagues suspected that the oxygen in interstellar space might be trapped in other compounds, preventing it from forming molecular oxygen. To find out, they exposed small water ice and silicate grains to pure oxygen gas, allowing the oxygen atoms to bind to the surface of the grains. They then heated the grains and observed how much energy it took for oxygen atoms to escape from these bonds.



Courtesy of Gianfranco Vidali

Shown above is a schematic of the apparatus used by researchers at Syracuse University to study oxygen molecules in interstellar space.

They measured the binding energy of water ice as 0.14 electron volts, and the binding energy of silicate as 0.16 electron volts. Older astronomical models that had predicted vast amounts of O^2 throughout the universe had assumed that the temperature of dust clouds would be high enough to free oxygen from dust grains, allowing it to form molecular oxygen, because the binding energy of the two compounds in question was thought to be less than half of what He's team came up with. Hence, for oxygen atoms to be able to escape from those compounds and subsequently form molecules, dust clouds would have to be much hotter than they presumably are. He's team's finding brings astronomers' models in line with their observations — molecular oxygen should indeed be rare.



Courtesy of Gianfranco Vidali

This is the actual apparatus used by the researchers to measure the binding energy of water ice and silicate. They found that the temperature of dust clouds would not be high enough to free oxygen from dust grains and form molecular oxygen.

In the Orion Nebula, it is thought that a massive shock wave provided the necessary kinetic energy to overcome the binding energy and free the oxygen molecules. They could then bind to each other, forming the small amount of molecular oxygen that astronomers find.

Oxygen on Earth

If molecular oxygen is so rare in the universe, how did so much of it end up here on Earth? In fact, for much of Earth's history, O_2 was just as rare here as anywhere else. When ancient microbes formed during the Archaean eon (3,800 to 2,500 million years ago), they lived anaerobically. But then, about 2.7 billion years ago, tiny organisms called cyanobacteria, or blue-green algae, evolved a process called photosynthesis. They used sunshine, water and atmospheric carbon dioxide to produce carbohydrates to serve their energy needs. A byproduct of this process was molecular oxygen.

Steve Gschmeissner/Getty Images

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The O_2 collected in the atmosphere, becoming significant about 2.45 billion years ago — a period scientists call the Great Oxidation Event. Another billion years later, there was enough O^2 in the atmosphere to allow animals to evolve. To this day, plants perform the process begun by their ancient forebears of supplying Earth with breathable, molecular oxygen.

Discussion Questions

Are there any sites in the cosmos, such as a black hole or a supernova, where it might make sense to look for O_2?

It is said above that breaking things up requires more kinetic energy — energy of motion. When you add heat, where would you look to see the increased motion?

Journal Articles and Abstracts

(Researchers' own descriptions of their work, summary or full-text, on scientific journal websites.)

He, Jiao, et al. "A New Determination of the Binding Energy of Atomic Oxygen on Dust Grain Surfaces: Experimental Results and Simulations." *Astrophysical Journal*, March 10, 2015: iopscience.iop.org/0004-637X/801/2/120/pdf/0004-637X_801_2_120.pdf.

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Croswell, Ken. "Why there is so little breathable oxygen in space." *Science* (May 5, 2015) [accessed May 18, 2015]: news.sciencemag.org/chemistry/2015/05/why-there-so-little-breathable-oxygen-space.

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