Search for Baryonic Matter in Intergalactic Space

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Searching for Baryonic Matter in Intergalactic Space

Two kinds of matter exist in the universe: mysterious dark matter, and normal—or baryonic—matter. Dark matter, which neither emits nor reflects light, is an exotic form of matter that is only detected via its gravitational influence. Baryonic matter is a particle physics classification of matter made of atomic nuclei, composed of protons and neutrons. It is the ordinary matter that makes up the stars, planets, gas, dust, and us.

According to scientists studying the afterglow of the Big Bang, dark matter was about five times more abundant than baryonic matter in the early universe. Although the ratio of dark to baryonic matter should remain constant over time, observations of galaxies in the nearby, modern universe can account for only a fraction of the ordinary matter expected. The rest must be found elsewhere.

Now, in an extensive search of the local universe by Hubble, astronomers have definitively found about half of the missing “normal” matter in the extremely dilute gas that surrounds and stretches between the galaxies. This gas, or intergalactic medium, is believed to extend unevenly throughout all of space.

Intergalactic space might intuitively seem to be empty, but researchers have known for decades that it is home to gas that is not in condensed form like in stars and galaxies. Charles Danforth and Mike Shull of the University of Colorado have taken the most detailed census of this important component of the universe, and have shown that the intergalactic medium is in fact the reservoir for most of the normal, baryonic matter in the cosmos.

Their observations were taken along sight lines to 28 active galactic nuclei, which are the cores of distant galaxies with active black holes made extremely luminous by the gravitational energy released by matter falling into them. The intrinsically brightest active galactic nuclei are called “quasars.” Danforth and Shull used their 28 active galactic nuclei—the majority

Known as the Hubble Ultra Deep Field, this million-second-long Hubble exposure taken in 2004 shows a universe full of galaxies. These galaxies, however, contain only a fraction of the baryonic, or normal, matter in the universe. Astronomers using Hubble to probe the local universe have definitively found about half of the missing normal matter in the extremely dilute gas that surrounds and stretches between the galaxies.
of which were quasars—as lighthouses to pierce the darkness and probe the so-called “cosmic web,” the complex scaffolding of matter that theory suggests occupies the seemingly invisible spaces between galaxies.

Although Danforth and Shull’s “baryon census” produced an outcome similar to Hubble results by Todd Tripp and colleagues in 2000, Tripp’s program was based on only one quasar sightline and has thus been greatly extended and put on a much firmer statistical footing by Danforth and Shull.

Searching for dilute baryonic matter in the nearby universe was one of the key projects identified for Hubble when the telescope was launched in 1990. The best way to observe this local gas is through ultraviolet spectroscopy. Danforth and Shull used the ultraviolet capability of Hubble’s Space Telescope Imaging Spectrograph (STIS), as well as NASA’s Far Ultraviolet Spectroscopic Explorer (FUSE), to probe the local intergalactic medium by looking at quasars. As it travels across the universe, some of the quasar light is absorbed by intervening bands of baryonic matter called “filaments.” This matter leaves spectral “fingerprints” at known colors, or “wavelengths,” that are characteristic of the types of atoms absorbing the light and also their line-of-sight distances. Because the Earth’s atmosphere absorbs ultraviolet light, these observations cannot be accomplished with ground-based telescopes.

**Taking Core Samples**

To conduct a census, the researchers needed enough deep sight lines, or core samples, to have a good representation of the intergalactic medium. They used the bright light from the quasars to penetrate 650 filaments of neutral hydrogen (a bound proton and electron) in the cosmic web, and produced a limited, but tantalizing three-dimensional probe of intergalactic space. Eighty-three filaments were found laced with highly ionized oxygen, in which five electrons have been stripped away. The presence of this highly ionized oxygen (and other elements) between the galaxies is believed to trace large quantities of invisible, hot, ionized hydrogen.
How much matter to look for?

Astronomers know how much matter to look for in two independent ways, and they both have to do with phenomena that occurred in the Big Bang. Deuterium, which is a heavy form of hydrogen, was cooked up in the first three minutes of the Big Bang. It was created only in the Big Bang, and not subsequently, unlike most other elements that are formed in stars. By measuring the amount of deuterium left over today relative to ordinary hydrogen, astronomers determine a ratio that tells how many baryons were present just after the Big Bang.

The second way, which is completely independent, involves studying sound waves from the Big Bang as measured by the cosmic microwave background. Most recently, NASA’s Wilkinson Microwave Anisotropy Probe (WMAP) performed some very detailed studies of these sound waves and confirmed that approximately 4.6 percent of all the mass/energy in the universe had to be in the form of baryons. The rest is in the form of dark matter and in dark energy, which is a mysterious, repulsive form of gravity. Of the 4.6 percent that is baryonic matter, less than 10 percent of that is locked up in galaxies. The rest must be found elsewhere.

Scientists believe that a specific mix of elements resides in intergalactic space. Although astronomers can’t detect the invisible, ionized hydrogen directly, oxygen in its ionized state can be detected. The oxygen accompanies the hydrogen, so scientists can deduce the existence of ionized hydrogen by finding the ionized oxygen. The oxygen “tracer” was probably created when exploding stars in galaxies spewed the oxygen back into inter-
galactic space, where it mixed with the pre-existing hydrogen via a shockwave that heated the oxygen to very high temperatures. These vast reservoirs of ionized hydrogen have escaped direct detection because they lack a signature in visible light and are too cool to be seen in x-rays. The oxygen has thus served as an important “proxy” for ionized hydrogen.

The 83 filaments laced with ionized oxygen also provided conclusive evidence that heavy elements from supernova explosions were blown out into very deep space, probably by galactic winds. Unlike hydrogen and helium, heavy elements were not born in the Big Bang, but in the interiors of stars. The evidence suggested that these elements have traveled several million light-years. The researchers stressed that the significance of these findings was not only in counting the baryons—
it was also determining how far from the galaxies they traveled and in what quantity. The team also found that about 20 percent of the baryons reside in the voids between the web-like filaments. Within these voids could be faint dwarf galaxies or wisps of matter that could turn into stars and galaxies in billions of years.

Non-baryonic dark matter is believed to collapse into filamentary structures, like huge spider webs, under the influence of gravity. Once collected, the dark matter exerts a gravitational force on the baryonic gas, pulling it into the cosmic filaments that then become visible to Hubble. The baryonic matter thus traces the underlying, invisible skeleton of dark matter. By uncovering the scaffolding of the universe, astronomers are also learning how galaxies formed and evolved.

This process is not very efficient. Only about 10 percent of the total baryonic matter is sufficiently condensed by gravity to form stars and galaxies. More than 90 percent was left between the galaxies. Some of this matter in intergalactic space could continue to fall into our galaxy and others; so the Milky Way still has matter falling in from intergalactic space and is still in the process of assembling.

**Looking Ahead**

Before Hubble, astronomers had found only about 10 percent of the baryonic matter in the local universe. Now, with this latest Hubble finding, they can account for roughly half. Taking advantage of the much greater ultraviolet sensitivity of the Cosmic Origins Spectrograph (COS), which astronauts will install on Hubble in 2009, scientists will be able to observe fainter, more distant objects. It is anticipated that COS could find another 10 to 20 percent of the baryonic matter in weak filaments of the cosmic web.

Probing the vast cosmic web will be a key goal for the COS, which will make possible more robust, more detailed, and significantly more numerous core samples of the cosmic web. COS will be up to 30 times more sensitive than STIS, allowing astronomers to use fainter quasars to look along many more sight lines, thus building up a more complete picture of the cosmic web, its constituents, and its physical state. Together with the larger astronomical community, the COS team hopes...
to observe at least 100 additional quasars and build up a survey of more than 10,000 hydrogen filaments in the cosmic web, many laced with heavy elements from early stars. After COS has completed its work, the percentage of missing baryons should be greatly reduced from what it is today.

Shull predicts that in another 10 to 15 years, astronomers will probably have to look in the x-ray range to find the rest. With much larger x-ray telescopes, they will be able to take spectra of even more highly ionized oxygen and other gas.

COS will have other critical work to do besides taking the measure of the intergalactic medium and the cosmic web. For example, numerous quasar sight lines selected by astronomers will intentionally traverse the gaseous halos of distant but known galaxies. This will provide a direct indicator of the steady production of heavy elements through cosmic time, as generation after generation of stars are born and die. Astronomers can then observe the processes involved in galaxy assembly, and the feedback mechanisms that transfer gas in both directions between galaxies and the intergalactic medium.

This is simulation of a slice of the cosmic web. The filaments are made mostly of dark matter located in the space between galaxies. Hubble and Far Ultraviolet Spectroscopic Explorer probed the structure of intergalactic space to look for missing ordinary matter, called baryons, that is gravitationally attracted to the cosmic web. (Figure credit: E. Hallman et al., University of Colorado.)
Further Reading


Charles Danforth is a research scientist at the University of Colorado at Boulder. He grew up in northern New Hampshire, attended Swarthmore College, and received his Ph.D. from The Johns Hopkins University in 2003. At Johns Hopkins, he was active in using space-based ultraviolet instruments to study the interstellar matter, both in supernova remnants in the Milky Way galaxy, as well as larger, more energetic structures in the nearby Magellanic Clouds. After grad school, he applied his expertise with far-UV spectral data to the local intergalactic medium using both FUSE and Hubble observations of distant quasars. He looks forward to continuing this research with new, state-of-the-art data from the Cosmic Origins Spectrograph, a new instrument to be installed during the Hubble Servicing Mission 4 in 2009. His other interests include galactic structure, supernova remnants, cosmology, and hot stars. In his spare time, Charles enjoys long-distance running, mountaineering, backcountry skiing, and rock climbing.

Dr. Michael Shull is a professor of astrophysics at the University of Colorado at Boulder. He was raised in Fargo, North Dakota and St. Louis, Missouri. Dr. Shull received his B.S. in physics from Caltech, and his Ph.D. in physics from Princeton University. His theoretical and astronomy interests include studies of gas between the stars and galaxies, galaxy formation, the first stars, supernovas, and quasars. Shull is a co-investigator on the science team for the Cosmic Origins Spectrograph (COS), a new ultraviolet instrument for the Hubble Space Telescope. COS will provide a tenfold increase in power for studies of the distant intergalactic medium and the evolution and spatial distribution of missing matter and heavy elements.