

The enduring significance of the Hubble Deep Field

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4 August 2021

Among the most enduring scientific achievements of the Hubble Space Telescope is the Hubble Deep Field image, which revealed a far richer and more complex structure of the cosmos than ever imagined. NASA is this week celebrating the advance enabled by the Deep Field and its subsequent scientific results.

The Hubble Deep Field was taken over 10 consecutive days between December 18 and 28, 1995. It consists of 342 separate exposures taken over more than 140 hours by the Wide Field and Planetary Camera 2 (WFPC2), all of which are in a small region in the constellation Ursa Major (of which the Big Dipper is a part). Looking through telescopes on Earth's surface, this is one of the most featureless areas of the night sky, with almost zero dust from the Milky Way and only a handful of stars. The area observed encompasses a tiny 1 part in 24 million of the total sky.

At the time, it was unclear to astronomers what would actually be seen. There were many like astrophysicist John Bahcall, who argued in a paper in the journal *Science* that Hubble would not be any better than ground-based instruments at observing distant galaxies. This position was strengthened immediately after Hubble's launch in 1990, when the first images showed that the telescope had an optical defect that put the whole project in jeopardy. It was only after the optics were corrected during Hubble's first servicing mission, undertaken by astronauts carried to orbit by the Space Shuttle Endeavour, that the telescope began producing sharper images than could be acquired from the ground.

In the immediate aftermath of the fix, NASA and the Space Telescope Science Institute, which is the science operations center for Hubble, used the space telescope for a Medium Deep Field survey to take advantage of the improved imaging capabilities. During this campaign, the WFPC2 took images of random fields

while other instruments performed scheduled observations. The most intriguing of these images revealed hints of objects that seemed much further away than Hubble's actual targets and were in areas of otherwise dark sky.

To follow up, Robert Williams, the director of Hubble's operations, decided to use what is known as director's discretionary time to perform a much longer exposure, to more systematically peer into the seeming darkness. For 10 days, Hubble was directed to stare at this largely unobserved and previously thought uninteresting part of the sky.

The results turned out to be spectacular. The first Hubble Deep Field was presented at a meeting of the American Astronomical Society in January 1996. "We were all stunned," noted one astronomer present at the meeting. The imagery showed nearly 3,000 distinct galaxies of all shapes and sizes, some of which were 4 billion times fainter than what the human eye can see. The image made clear that the Universe is not empty in areas where ground-based telescopes then saw very little, but rather teeming with galaxies and other cosmic structures in every direction.

It was understood that through these images, Hubble was not just probing space, but also time. Even light, which is more than 1.3 million times faster than the average passenger plane, can take millions or even billions of years to cross the vast distances between galaxies and galactic clusters. Observing such distant objects means that we are seeing them as they were millions and billions of years ago, times which constitute definite nodal points in the history of the Universe.

The field of observational cosmology was revolutionized as astronomers absorbed these insights. While very bright and compact objects known as

quasars had been observed at far distances (“at high redshifts” in astronomical parlance), there were few such distant galaxies known before the Hubble Deep Field. For the first time, astronomers directly observed galaxies from 12 billion years ago, only a billion or so years after the Big Bang.

The sheer number of galaxies in the deep field images also helped confirm evolving conceptions of star formation rates across the Universe’s history. The data show that this rate peaked 8-10 billion years ago, and has fallen by about an order of magnitude since then, largely a product of the decreasing density of the Universe and the decreasing frequency of galactic mergers, which trigger episodes of star formation.

With the success of the original Deep Field image, numerous further observations were carried out. These include the Hubble Deep Field South (1998), the Hubble Ultra Deep Field (2004), the Hubble Deep Field-Infrared (2009) and the Hubble eXtreme Deep Field (2012). In each, thousands of galaxies have been imaged, again confirming that galaxies are everywhere, and probing more deeply the structure of the cosmos.

Starting in 2013 and continuing through 2017, a new campaign began, combining the observational capabilities of Hubble and its sister Great Observatories, the Spitzer Telescope and the Chandra X-ray Observatory, in the Frontier Fields project. The extensive campaign resulted in 12 new deep field images that detailed the farthest reaches of the Universe across the electromagnetic spectrum—visible, infrared, ultraviolet and x-rays—providing insights that each of the telescopes separately would never been able to achieve.

One of the most significant observations was of the Abell 370 galactic cluster, which was first observed in the 1980s to act as a gravitational lens. Gravitational lensing is a prediction of general relativity that the path light travels is bent by the gravity of a massive object such as a star or galaxy. When a whole galactic cluster acts as a lens, as in the case of Abell 370, it effectively turns into a cosmic-scale telescope that magnifies and brightens objects behind it in a way that is beyond the imaging capabilities of the best telescopes, a property used to great effect by Hubble, Spitzer and Chandra.

There is also an interesting social aspect to the deep field experiments. The amount of data collected in each necessitated a far broader collaboration by astronomers

than ever previously conceived to process and understand the physics contained within, both nationally and internationally. Alongside, the development of the internet allowed massive public and open datasets to be built, which has allowed the broader working class to engage with deep questions of astronomy and cosmology in a way that had been impossible before the 1990s.

The significant investment of telescope time and scientific expertise in generating deep fields makes them rare milestones, but they are absolutely critical to our understanding of the Universe. Many other observations to map far distant galaxies and place them within broader structures are ongoing, such as the Sloan Digital Sky Surveys, which make detailed three-dimensional maps of the Universe on scales of galactic clusters and larger. Through deep fields, humanity sees both deep into space and far back in time, piecing together the history of the stars and our place within cosmic development.



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