FM 22:
The Frontier Fields: Transforming our understanding of cluster and galaxy evolution

Astronomy in Focus, XXIXB, Focus Meeting 22
XXIXth IAU General Assembly, August 2015
Piero Benvenuti, ed.

doi:10.1017/S1743921316006712

The Frontier Fields: Past, Present, and Future

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Abstract. Exceptionally deep observations of the distant universe with the Hubble Space Telescope have consistently pushed the frontiers of human knowledge. How deep can we go? What are the faintest and most distant galaxies we can see with the Hubble Space Telescope now, before the launch of the James Webb Space Telescope? This is the challenge taken up by the Frontier Fields, a director's discretionary time campaign with HST and the Spitzer Space Telescope to see deeper into the universe than ever before. The Frontier Fields combines the power of HST with the natural gravitational telescopes of high-magnification clusters of galaxies to produce the deepest observations of clusters and their lensed galaxies ever obtained. I will review the original goals of the Frontier Fields program and its progress over the last several years. In addition to pushing forward the study of the most distant galaxies, the Frontier Fields have been transformative in the study of galaxy clusters and their lensing properties. Finally, I will discuss the prospects for studying galaxies at cosmic dawn with JWST, extremely large ground-based telescopes, and future space missions over the next decade and beyond.

Keywords. gravitational lensing; galaxies:clusters, galaxies: high-redshift; surveys

1. Introduction

Exceptionally deep observations of the distant universe with the Hubble Space Telescope (HST) have consistently pushed the frontiers of human knowledge. A succession of observing programs with each generation of HST detectors, in concert with the other NASA Great Observatories (Spitzer Space Telescope and Chandra X-ray Observatory), have probed the star-formation and assembly histories of galaxies through $> 95\%$ of the universe's lifetime. These observations have been made publicly available to the astronomy community, enabling a wide range of science and ancillary observing programs. Here we present the Frontier Fields a director's discretionary time campaign to observe six strong-lensing clusters and six parallel fields and detect the faintest galaxies ever observed.

With the launch of the James Webb Space Telescope (JWST) still several years away, and no new servicing missions to HST planned, significant progress on understanding the first billion years of the universe with the remaining HST years poses a major challenge. The Hubble Deep Fields Initiative science working group (convened by STScI Director M. Mountain in 2012) recommended a new strategy, namely to use massive clusters of galaxies as 'cosmic telescopes'. Very massive clusters of galaxies are the most massive structures in the universe, bending space-time to effectively create efficient gravitational lenses. The light from galaxies behind these natural telescopes experience magnification factors of a few within a few arc-minutes of the cluster cores, and magnifications~ 10 or greater within smaller windows along the critical curves. Therefore, HST observations of these strongly-lensed fields can probe galaxies as intrinsically faint or fainter than those detected in the HUDF in a much shorter exposure time – provided those galaxies fall within the high magnification windows.

2. Science Goals

The charter for the Hubble Deep Fields Initiative recommended a 840 orbit HST program to image six strong-lensing clusters and six associated parallel fields with ACS and WFC3/IR in seven optical-NIR broadband to 5σ depths $\sim$28.7-29th AB mag. The four primary science aims for the resulting Frontier Fields are:

1. to reveal populations $z = 5 - 10$ galaxies that are > 10 times fainter than any presently known, the key building blocks of $\sim L^*$ galaxies in the local universe.

2. to characterize the stellar populations of faint galaxies at high redshift and solidify our understanding of the stellar mass function at the earliest times.

3. to provide, for the first time, a statistical morphological characterization of star forming galaxies at $z > 5$.

4. to find $z > 8$ galaxies stretched out enough by foreground clusters to measure sizes and internal structure and/or magnified enough for spectroscopic follow up.

These fields will greatly expand the deep sky available to JWST in its first years, and refine the cluster lensing technique to extend its reach out to the first galaxies. In the years leading up to JWST's launch, the Frontier Fields will enable new insight to early galaxy evolution with the Hubble and Spitzer space telescopes, and prepare the astronomical community to make the best use of JWST on some of the most compelling problems in astrophysics. In addition, a number of other important astronomical questions are being addressed with these fields, also presented at this IAU focus meeting. These include the study of lensed galaxies at $1 < z < 4$, the development of lensing models, the study of the dark matter and substructure distribution in massive clusters, galaxy evolution within clusters, and high-redshift supernovae and transients.

3. Observations

The Frontier Fields clusters are Abell 2744, MACSJ0416.1-2403, MACSJ0717.5+3745, MACSJ1149.5+2223, AbellS1063 (also known as RXCJ2248.7-4431), and Abell 370. These clusters are at redshifts between 0.3 and 0.55, and are among the most massive known clusters at these redshifts. The fields were selected based up (1) their lensing properties, quantified by the number of high-redshift galaxies expected to be detected within the HST WFC3/IR field of view; (2) low zodiacal light and Galactic extinction; (3) suitability of the parallel field positions; (4) suitability for ground-based follow-up; (5) existence of ancillary data; and (6) HST, Spitzer, and JWST observability.

Very deep high-spatial resolution imaging with HST is required to achieve the Frontier Field science goals of detecting and characterizing faint lensed and unlensed galaxies in the early universe. Deep optical and near-infrared imaging in seven bandpasses from 0.4-1.6 microns (ACS F435W, F606W, F814W, WFC3/IR F105W, F125W, F140W, F160W) will be used to identify high-redshift galaxies ($z > 4$) using the Lyman break drop-out technique. Deep Spitzer IRAC imaging at 3.6 and 4.5 micron to $\sim$ 26.6 AB 5σ depths will place additional constraints on galaxy redshifts. Spectral energy distribution fitting of the multi-wavelength photometry from the combined HST and Spitzer imaging will provide photometric redshifts, and estimates of the galaxy stellar masses and recent star-formation histories.

The observations of the Frontier Field parallel fields are designed to be the second-deepest HST 'blank' field observations, slightly deeper than the Ultra Deep Field parallel

Figure 1. Ther first Frontier Field cluster Abell 2744. (NASA/ESA/STScI)

fields, and ~ 1 magnitude shallower than the Ultra Deep Field 2012. The Frontier Field cluster observations have the same exposure times as the parallel fields, and similar observed depths (modulo the contribution to the foreground by the cluster ICL and galaxies). However, the intrinsic depths for background galaxies lensed by the clusters are deeper than the parallel fields, with typical magnifications across the cluster pointings $\sim 1.5 - 2$ and small areas magnified by factors as large as $> 10 - 100$.

The Frontier Fields implementation team is providing rapid images release for the Hubble data. Every incoming exposure is visually inspected and flagged for artifacts, including satellite trails, persistence, and scattered light within a few days of acquisition. Intermediate v0.5 stacked and drizzled images products are produced with standard archival retrievals, at 30 and 60 mas pixel scales, with major artifacts masked. The v1.0 "best effort" image products are released with several weeks of the completion of the observing epoch for each field pair at a given orient and camera configuration.

In addition to releasing the raw and reduced data products, the Frontier Fields implementation team has coordinated a community effort to provide the best-quality lensing models for each cluster to the public. Prior to the first Frontier Fields observations, five lensing teams were selected to create deflection and magnification maps based on pre-existing data. The teams shared input data, multiply-imaged sources, and redshifts, such that differences between output models reflect differences in the techniques rather than the assumptions. Based on the recommendations of the mid-term review committee for the Frontier Fields, new maps based on the much deeper Frontier Fields data and new spectroscopic observations are being commissioned. These models are publicly available via MAST, and may be accessed through an interactive tool to obtain the magnifications and uncertainties for specific objects.

4. The Future

The Hubble Frontier Fields observations of the last two clusters and parallel fields are slated to complete by September 2016, roughly two years before the launch of JWST. Although not yet complete, the Frontier Fields has already met it primary science goals of pushing the boundaries of knowledge about the high-redshift universe and detecting galaxies fainter than any we have seen before. These data has also provided unprecedented maps of dark matter in the most massive structures in the universe, and discovered the first multiply-imaged supernova. The combination of strong-lensing clusters such as the Frontier Fields with the James Webb Space Telescope will also us to peer even farther and fainter into the universe.

For more information:
http://www.stsci.edu/hst/campaigns/frontier-fields/
http://www.stsci.edu/hst/campaigns/frontier-fields/documents/HDFI_SWGReport2012.pdf
http://www.stsci.edu/hst/campaigns/frontier-fields/documents/FF_MidTermReview.pdf
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