Extracting Faint Signals Behind Bright Sources From CLASH Imaging Using Fourier Analysis

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Abstract. With the combination of deep *Hubble Space Telescope* Imaging and magnification due to gravitational lensing, the CLASH program offers an unprecedented opportunity to search for supernovae at high redshifts and detect some of the most distant galaxies as well. Unfortunately, the cluster field suffers from a high abundance of bright foreground sources and high background due to intra-cluster light. To overcome these difficulties, we have developed a method of modeling and subtracting bright foreground light in the clusters using Fourier analysis. In this paper, I will present preliminary results based our method, which significantly increases the effective depth of the images, and efficiently characterizes distant background signals in the clusters.

Introduction

The Cluster Lensing and Supernova survey with Hubble (CLASH) is one of three *Hubble* Multi-Cycle Treasury (MCT) programs selected in 2009, which observes massive galaxy clusters at intermediate redshifts. With the combination of deep *Hubble Space Telescope* Imaging and magnification due to cluster gravitational lensing, the CLASH program has four main science goals: (1) to measure the profiles and substructures of dark matter in galaxy clusters with unprecedented precision and resolution, (2) to discover and monitor distant supernovae in the cluster fields through a staggered program of multi-wavelength observations, (3) to characterize some of the most distant galaxies yet discovered, and (4) to study the internal structure and evolution of the galaxies in and behind these intermediate clusters [1].

Unfortunately, the region of clusters is a crowed field and foreground cluster members are usually much brighter than distant background sources. Moreover, a substantial fraction of stars in clusters are not gravitationally bound to any particular cluster galaxy. These stars constitute the so-called intra-cluster light (ICL). The ICL is distributed around the central dominated galaxy of the cluster and extends to several hundred *kpc* away from the cluster center. This diffuse light contributes to a relatively high background, which suppresses the weak signals of sources in the early universe [2]. Therefore, in order to detect and characterize these faint background sources, an efficient method is needed to model and subtract the foreground light in the clusters.

In this paper, we report a new method of modeling and subtracting the foreground light in the clusters using Fourier analysis, which was developed by our group independently. The outline of the paper is as follows. In subsequent two sections, we describe the imaging data of Hubble Space Telescope in CLASH and our modeling, respectively. A conclusion is drawn in the last section.

HST Imaging Data in CLASH

The CLASH sample contains 25 clusters of galaxies with z = 0.18-0.89 and global X-ray temperatures greater than 5 keV. Twenty of these clusters were selected for their X-ray surface brightness symmetry indicating relaxed clusters, and the remaining five were specifically selected to

Table 1 - The CLASH Cluster Sample and *HST* Observing Plan

Cluster	α_{J2000}	δ_{J2000}	z_{Clus}	HST Cycle	Orbits	Program ID
Abell 209	01:31:52.57	- 13:36:38.8	0.206	19	20	12451
Abell 383	02:48:03.36	- 03:31:44.7	0.187	18	20	12065
MACS0329.7-0211	03:29:41.68	- 02:11:47.7	0.450	19	20	12452
MACS0429.6-0253	04:29:36.10	- 02:53:08.0	0.399	20	20	12788
MACS0744.9+3927	07:44:52.80	+39:27:24.4	0.686	18	17	12067
Abell 611	08:00:56.83	+36:03:24.1	0.288	19	18	12460
MACS1115.9+0129	11:15:52.05	+01:29:56.6	0.352	19	20	12453
Abell 1423	11:57:17.26	+33:36:37.4	0.213	20	20	12787
MACS1206.2-0847	12:06:12.28	- 08:48:02.4	0.440	18	20	12069
CLJ1226.9+3332	12:26:58.37	+33:32:47.4	0.890	20	18	12791
MACS1311.0-0310	13:11:01.67	- 03:10:39.5	0.494	20	20	12789
RXJ1347.5-1145	13:47:30.59	- 11:45:10.1	0.451	18	15	12104
MACS1423.8+2404	14:23:47.76	+24:04:40.5	0.545	20	17	12790
RXJ1532.9+3021	15:32:53.78	+30:20:58.7	0.345	19	20	12454
MACS1720.3+3536	17:20:16.95	+35:36:23.6	0.391	19	20	12455
Abell 2261	17:22:27.25	+32:07:58.6	0.224	18	20	12066
MACS1931.8-2635	19:31:49.66	- 26:34:34.0	0.352	19	20	12456
RXJ2129.7+0005	21:29:39.94	+00:05:18.8	0.234	19	20	12457
MS2137-2353	21:40:15.18	- 23:39:40.7	0.313	18	18	12102
RXJ2248.7-4431	22:48:44.29	- 44:31:48.4	0.348	19	20	12458
MACS0416.1-2403	04:16:09.39	-24:04:03.9	0.42	19	20	12459
MACS0647.8+7015	06:47:50.03	+70:14:49.7	0.584	18	18	12101
MACS0717.5+3745	07:17:31.65	+37:45:18.5	0.548	18	17	12103
MACS1149.6+2223	11:49:35.86	+22:23:55.0	0.544	18	18	12068
MACS2129.4-0741	21:29:26.06	- 07:41:28.8	0.570	18	18	12100

Table 2 – CLASH Observing Information

Camera/Channel	Filter	Orbits	ExposureTime [sec]	10σ Limit [ABmag]	5σ Limit [AB mag]
WFC3/UVIS	F225W	1.5	3558	25.7	26.4
WFC3/UVIS	F275W	1.5	3653	25.7	26.5
WFC3/UVIS	F336W	1.0	2348	25.9	26.6
WFC3/UVIS	F390W	1.0	2350	26.5	27.2
ACS/WFC	F435W	1.0	1984	26.4	27.2
ACS/WFC	F475W	1.0	1994	26.8	27.6
ACS/WFC	F606W	1.0	1975	26.9	27.6
ACS/WFC	F625W	1.0	2008	26.4	27.2
ACS/WFC	F775W	1.0	2022	26.2	27.0
ACS/WFC	F814W	2.0	4103	27.0	27.7
ACS/WFC	F850LP	2.0	4045	26.0	26.7
WFC3/IR	F105W	1.0	2645	26.6	27.3
WFC3/IR	F110W	1.0	2415	27.0	27.8
WFC3/IR	F125W	1.0	2425	26.5	27.2
WFC3/IR	F140W	1.0	2342	26.7	27.4
WFC3/IR	F160W	2.0	4920	26.7	27.5

have large Einstein radii. All of the CLASH clusters have Chandra observations, and 15 were also observed with XMM. 18 of the clusters show strong lensing arcs [1].

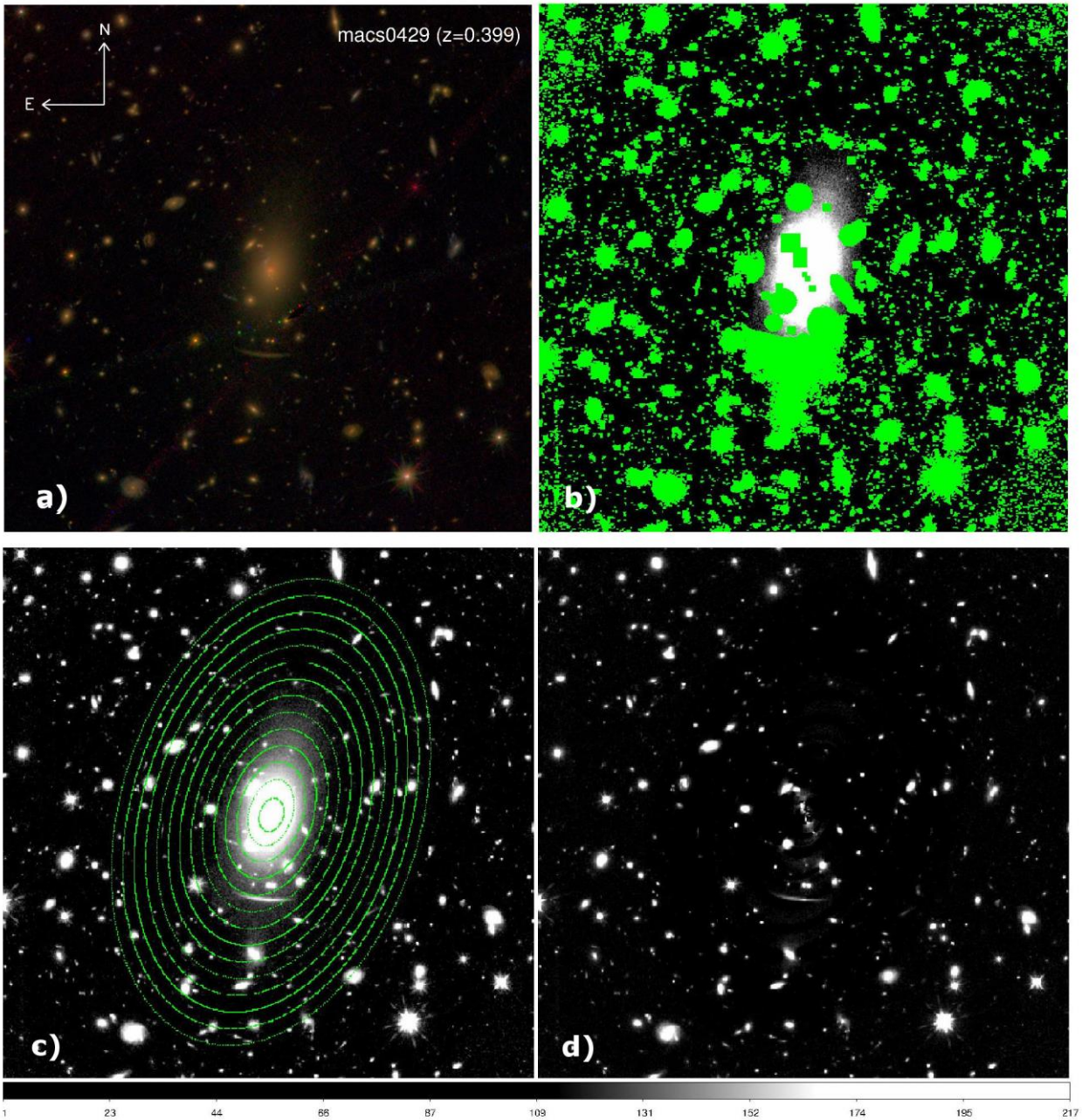

Fig. 1 An example of modeling and subtracting foreground dominated signal (MACS 0429.6-0253). a) Pseudo-color cut-out image made with observed *B, V, z* images. b) H-band cut-out image overlapped with the '*MASK*' image. c) H-band cut-out image overlapped with approximately elliptical isophotes (green ellipses). d) H-band cut-out image after subtracting our model created by using Fourier analysis. Each frame has 1800×1800 pixels.

Table 1 presents the names of sample clusters, positions, redshifts, and *HST* observing cycle and orbits. *HST* observes these clusters with totally 16 filters by the Advanced Camera for Surveys (ACS, [3]) and the Wide Field Camera 3 (WFC3,[4]), respectively. With continuous sampling of the broad wavelength range from the NUV to NIR that is enabled with WFC3 and ACS, The CLASH team we can obtain very accurate photometric redshifts of galaxies in each cluster, which helps to distinguish foreground light from faint background sources. In Table 2, we list all channels, filters, exposure time, and the limiting magnitudes for CLASH imaging. The image co-addition and alignment onto a grid with 0.065 arcsec/pixel is performed with an automated pipeline based on *MosaicDrizzle* [5]. Object detection and photometry is then accomplished using *Sextractor* [6] in dual image mode.

Modeling and Subtraction of Bright Foreground Source

In this section, we illustrate the power of our modeling and subtracting foreground dominated signals with an example, MACS 0429.6-0253 (MACS0429, thereafter). As described above, CLASH observations cover 16 filters. The background levels in different filters are different. First, we use previously developed methods [7,8] to perform the background subtraction in each filter independently. To obtain accurate information of the sky background, we generate a 1800×1800 pixels background only image using *SExtractor* [6] by masking all the detected objects with counts above 1-σ noise in a frame smoothed by a circular Gaussian with a standard deviation σ = 3 pixel. A median filter with 201 × 201 pixels is then convolved with the unmasked pixels, after which second order Legendre polynomials are used to fit both rows and columns, respectively [7]. The fitted Legendre polynomials are then further smoothed using a circular Gaussian filter with σ = 9 pixel to obtain our final sky background model. We then subtract this model from the frame to obtain the background-free image.

In order to model foreground dominated source accurately, we mask other faint signals as illustrated in Panel b of Figure 1. We perform the Fourier analysis on each isophote of central dominated source. An ellipse is drawn to approximately match each isophote as illustrated in Panel c of Figure 1. The intensity along the ellipse is expanded in Fourier series

$$I(\theta) = I_0 + \sum (A_n \cos n\theta + B_n \sin n\theta) \tag{1}$$

where I_0 is the intensity averaged over the ellipse, and A_n and B_n are the higher order Fourier coefficients. This analysis starts from a first guess elliptical isophote defined by approximate values for the X and Y center coordinates, ellipticity and position angle. Using these values, the image is sampled along an elliptical path producing a one-dimensional intensity distribution as a function of position angle. The harmonic content of this distribution is analyzed by least-squares fitting. After modeling the isophote in each annulus, we subtract all fitted ellipses from the background-free image to obtain a residual image. As illustrated in the Panel d of Figure 1, our method is successful to remove bright foreground sources in the clusters, which significantly increases the effective depth of the images, and efficiently uncovers distant background signals in the centers of clusters.

Summary

The CLASH program offers an unprecedented opportunity to search for supernova at high redshifts and detect distant signals in the early universe. However, bright foreground light (mainly member galaxies and ICL) in the clusters prevents the detection and study of faint background sources. In this paper, we report a method of modeling and subtracting bright foreground sources. We perform the Fourier analysis on each isophote of foreground dominated galaxy in the clusters. After subtracting our modeled ellipses, faint sources behind foreground dominated galaxy are uncovered clearly. It crucially opens up the most magnified regions of the clusters.

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