Discovery of eight lensing clusters of galaxies

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Clusters of galaxies have a huge mass which can act as gravitational lenses. Galaxies behind clusters can be distorted to form arcs in images by the lenses. Herein a search was done for giant lensed arcs by galaxy clusters using the SDSS data. By visually inspecting SDSS images of newly identified clusters in the SDSS DR8 and Stripe 82 data, we discover 8 strong lensing clusters together with additional 3 probable and 6 possible cases. The lensed arcs show bluer colors than the member galaxies of clusters. The masses and optical luminosities of galaxy clusters interior to the arcs are calculated, and the mass-to-light ratios are found to be in the range of a few tens of $M_\odot/L_\odot$, consistent with the distribution of previously known lensing clusters.

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1 Introduction

Galaxy clusters are the largest gravitational bound systems in the universe, with a mass of about $10^{14} M_\odot$–$10^{15} M_\odot$. About $\sim$3% of such a huge mass comes from galaxies visible in optical, $\sim$15% of the mass exists in the form of diffuse hot intracluster gas detected in X-ray, and about $\sim$82% of mass is contributed from invisible matter, probably dark matter [1].

Galaxy clusters with such a mass have a huge gravity that can deflect lights of background sources, so that they act as lenses. When a background galaxy is located very close to the light-of-sight of a lens in the sky, it can be magnified to be a brighter object but distorted to form giant arcs or multiple images. The properties of lensed arcs, such as locations and shapes, depend on the mass distribution of the gravitational lens and are independent of the form of matter (luminous or dark, gas or stars). Therefore, the lensing effect is a unique tool to measure the total mass of a galaxy cluster. Such measured mass of galaxy clusters can be used to calibrate other observable mass proxies in optical and X-ray [2], which can be easily applied to a complete sample of galaxy clusters to calculate the mass function and then constraint cosmology parameters [3].

Previously, many efforts have been made to search for giant lensed arcs in various survey data based on samples of massive clusters, for example, Einstein Observatory Extended Medium Sensitivity Survey [4], Red-Sequence Cluster Survey data [5], Hubble WFPC2 data [6], Canada-France-Hawaii Telescope Legacy Survey data [7], Sloan Digital Sky Survey (SDSS) data [8–11], the Wisconsin-Indiana-Yale NOAO 3.5m telescope and the University of Hawaii 88 inch telescope data [12]. Up to now, about 318 strong lensing clusters of galaxies have been discovered.

Using the SDSS data, we identified two large samples of galaxy clusters, and then visually inspected the color images of the clusters to find new lensing systems. Our first effort was made by inspecting the color images of 39,668 clusters, from which we found 13 new lensing systems candidates [10]. They were classified as 4 almost certain lensing systems, from which we found 13 new lensing systems candidates [10]. They were classified as 4 almost certain lensing systems, 5 probably and 4 possible cases. Currently, 12 of these 13 systems have been confirmed as true lensing systems by spectroscopic observations [13–15]. The second effort was to view color images of 132,684 clusters, from which 98 lensing candidates were found [11]. They were classified as 13
Figure 1  SDSS images of 8 clusters with a field of view of 1.2′×1.2′. They are almost certain to be gravitational lensing systems. The negative images are also shown in the second rows to see the lensing features more clearly.
Table 1  Parameters of newly discovered lensing clusters of galaxies

| Cluster Position | z    | Richness | $\theta_e$ | $r$     | (g − r)$_{arc}$ | (g − r)$_{hess}$ | Sky region | Probability  | $M_e$      | $M_e/L_e$ |
|------------------|------|----------|------------|---------|-----------------|-----------------|------------|--------------|------------|-----------|
| 011107.2+134644  | 0.595| 25.00    | 8.8        | 22.14±0.14| 0.05±0.24       | 1.04±0.14       | DR8        | almost certain | 2.52      | 79.4      |
| 012237.5+011123  | 0.550| 29.18    | 6.5        | 22.46±0.28| 0.89±0.53       | 1.94±0.19       | Stripe 82  | almost certain | 1.25      | 35.2      |
| 022510.8−004707  | 0.380| 20.89    | 9.6        | 22.92±0.10| 0.89±1.63       | 1.52±0.09       | Stripe 82  | almost certain | 1.79      | 132.8     |
| 092049.9+452158  | 0.661| 51.98    | 4.1        | 20.59±0.05| 0.73±0.09       | 2.03±0.30       | DR8        | almost certain | 0.63      | 48.3      |
| 120535.4+411044  | 0.662| 94.30    | 3.4        | 20.65±0.06| 0.39±0.08       | 3.20±0.76       | DR8        | almost certain | 0.43      | 7.5       |
| 150924.7+390140  | 0.593| 20.59    | 3.0        | 22.03±0.14| 0.08±0.17       | 1.83±0.20       | DR8        | almost certain | 0.29      | 6.3       |
| 152559.9+084639  | 0.602| 50.23    | 3.4        | 22.16±0.12| −0.40±0.13      | 1.24±0.24       | DR8        | almost certain | 0.48      | 16.1      |
| 162320.3+215535  | 0.482| 23.85    | 6.0        | 20.89±0.11| 0.20±0.14       | 1.53±0.06       | DR8        | almost certain | 0.91      | 36.8      |
| 025932.5+001354  | 0.209| 58.00    | 14.8       | 19.81±0.21| 0.18±0.32       | 1.38±0.02       | Stripe 82  | probable       | 2.32      | 55.5      |
| 033304.7−065122  | 0.635| 151.62   | 8.9        | 22.29±0.22| −0.01±0.26      | 3.17±0.88       | DR8        | probable       | 2.81      | 25.4      |
| 231354.5−010449  | 0.546| 53.75    | 7.9        | 22.27±0.23| 0.31±0.35       | 1.87±0.31       | Stripe 82  | probable       | 1.83      | 45.3      |
| 021342.9−000359  | 0.693| 19.42    | 4.0        | 23.86±0.17| −0.13±0.20      | 1.32±0.11       | Stripe 82  | possible       | 0.64      | 69.4      |
| 023830.7+004855  | 0.406| 16.36    | 2.5        | 23.21±0.49| −0.42±0.54      | 1.55±0.08       | Stripe 82  | possible       | 0.13      | 17.9      |
| 032812.7+003309  | 0.471| 11.37    | 4.6        | 21.85±0.18| 1.65±0.67       | 1.73±0.20       | Stripe 82  | possible       | 0.52      | 34.9      |
| 140217.1+392820  | 0.602| 85.45    | 4.1        | 21.71±0.10| 0.50±0.15       | 1.86±0.15       | DR8        | possible       | 0.56      | 17.0      |
| 224140.9−005750  | 0.496| 30.63    | 2.6        | 21.90±0.25| −0.11±0.32      | 2.25±0.24       | DR8        | possible       | 0.18      | 10.0      |
| 234709.1−000457  | 0.263| 13.62    | 4.9        | 22.11±0.27| 0.24±0.32       | 1.02±0.03       | Stripe 82  | possible       | 0.32      | 45.7      |

Figure 1  continued
almost certain lensing systems, 22 probably and 31 possible cases, and 2 exotic systems. Among them, 16 candidates have been confirmed [16]. We found from this large sample that richer clusters have a higher probability to be lensing systems.

This paper is the third effort on the direction. Following our previous procedures [17–18], we first identify new high redshift clusters from the SDSS DR8 data and the SDSS Stripe 82 data, then check images of 66,033 cluster candidates newly identified from the SDSS DR8 and 46,663 candidates in the Stripe 82, and we find 17 candidates of strong lensing systems, among which 8 cases are almost very certain, and other 3 are probably and 6 are possible cases. In the following section, we introduce data of our galaxy cluster sample and present our results of lensing searches. We then discuss the redshift distribution, and estimated the masses of galaxy clusters interior to the arcs, and then discuss the mass-to-light ratio for galaxy clusters.

2 Data and Results

Searches for new strong lensing systems are critical for both individual and statistical studies of galaxy clusters. The probability for strong lensing is very low. Currently, only a few hundreds among hundred thousands of galaxy clusters are shown as lensing systems.

We recently identify a new sample of galaxy clusters at high redshifts from the SDSS DR8 and the Stripe 82. The SDSS survey data contain the photometric redshifts of galaxies with a uncertainty of 0.025–0.030 in the redshift range of \( z < 0.45 \) and with a larger at higher redshift, by which large cluster samples were obtained [17–18]. A cluster was recognized when the richness \( R_{L*} = \frac{L_{\text{total}}}{L^*} \geq 12 \) and the number of member galaxy candidates within a photometric redshift slice of \( z \pm 0.04(1 + z) \) and a radius of \( r_{200} \), \( N_{200} \geq 8 \) [18]. Here, \( r_{200} \) is the radius within which the mean density of a cluster is 200 times of the critical density of the universe, \( L_{\text{total}} \) is the total luminosity of member galaxies, \( L^* \) is the characteristic luminosity. Most of the identified clusters have a redshift of \( z < 0.5 \) because of the larger uncertainties of photometric redshift at higher redshift. To find more high redshift clusters, we adjust the photometric redshift slice to be \( z \pm 0.06(1 + z) \) and identify 66,033 cluster candidates of \( R_{L*} \geq 20 \) and \( N_{200} \geq 8 \) at \( z \geq 0.5 \). The Stripe 82 region of SDSS covering 235 deg\(^2\) has been observed 2 mag deeper than other SDSS regions [19]. We also identify clusters in the SDSS Stripe 82 region using the photometric redshifts given in Ref. [20]. By setting the photometric redshift slice of \( z \pm 0.04(1 + z) \), 46,663 cluster/group candidates have been identified with a lower threshold of \( R_{L*} = 10 \) in the redshift range.
Figure 3  SDSS images of 6 possible lensing clusters with a field of view of 1.2′×1.2′. The negative images are also shown in the second rows.
of $0.05 < z < 1$.

We visually inspect images of above newly identified clusters to search for lensed arcs. For clusters identified from SDSS DR8, we inspect the composite gri color images. For clusters in the Stripe 82 region, we inspect the black-white images. As done previously [10, 11], we search for arcs in images and consider them as lensed background galaxies by a few criteria:

1. The arcs must be located in the center of a cluster, and must have a smoothly curved shape with respect to one or two central bright galaxies. Using this criterion, we can exclude cases for possible overlapping of a few faint galaxies.
2. The arcs have bluer colors than the cluster member galaxies. This excludes possible faint member galaxies and ensures the arcs being high-$z$ star-forming galaxies.
3. The arcs have a good length-to-width ratio. A larger ratio means a higher probability of true lensed background galaxies.
4. To exclude possible edge-on blue spiral galaxies, the arcs must be faint and must not be associated with any bulges. Blue spiral arms of some spiral galaxies can mimic arcs, but they are usually extended from the central bulge and are symmetrically located at two sides of the bulge. We have carefully check these feature and exclude them from our sample.

Research efforts have been made by many international teams in the development of algorithms for an automatic search of the lensed arcs, involving a large amount of image processing and matching, for example [21]. We prefer the simple manual inspections with the above qualitative criteria, which is practically efficient and much less resource-consuming. In the images of about a hundred thousand galaxy clusters, 17 clusters show giant arcs, including 152559.9+084639 and 162320.3+215535, which were serendipitously discovered after publication of our catalog [11]. According to the goodness of arcs matching the above criteria, we empirically classify these 17 systems into three classes: almost certain lensing systems, probably systems, and possible cases. There are 8 almost certain systems, 3 probably and 6 possible cases, as listed in Table 1. The arcs have a separation of $\sim 2.5''$ – $14.8''$ with respect to central cluster galaxies, and most of them are bluer than the galaxies of clusters. We show the images in Fig. 1 for almost certain cases, in Fig. 2 and Fig. 3 for probable and possible cases, respectively.

3 Discussions

The newly found lensing clusters of galaxies on average have a higher redshift than the 318 known strong lensing clusters, as shown in Fig. 4. The previously known lensing clusters are collected from literature, such as [4, 6, 12–15, 22–24].

Based on the SDSS images and redshift data, we get the angular separations between the arcs and the bright central galaxies. Here, we assume the separation as being the Ein-

http://skyserver.sdss3.org/dr8/en/tools/chart/list.asp
http://cas.sdss.org/stripe82/en/tools/chart/list.asp

Figure 4  Upper: redshifts of our 17 lensing clusters are compared with the distribution of 318 known strong lensing clusters. Middle and lower: mass-to-light ratios and color ($g - r$) of our 17 lensing clusters of galaxies are compared with the values of 45 previously known lenses.
stein radius, and then estimate the mass within this radius. In a ΛCDM cosmology ($H_0=70\text{ km s}^{-1}\text{ Mpc}^{-1}$, $\Omega_m = 0.275$ and $\Omega_\Lambda = 0.725$, hereafter), the mass is

$$M(<\theta) = \frac{c^2\theta^2 D_s D_l}{4G D_h},$$

(1)

where $D_s$ and $D_l$ are the angular diameter distances of the source and lens from the observer, and $D_h$ is the angular diameter distance of the source from the lens. We calculate the total gravitational mass within the radius by assuming that the source has a redshift $z_s = 1.5$. The values of the estimated masses are listed in Table 1.

We obtain the total $r$-band luminosity within the assumed Einstein radius. We can calculate the mass-to-light ratios of the lensing clusters, as listed in the last column of Table 1. These mass-to-light ratios are a few tens of the Solar value, which indicate that there do exist a huge amount of invisible matter in galaxy clusters, at least in the region inside the arcs. In Fig. 2 we compared the mass-to-light ratios for our 17 lensing clusters with the values estimated from arcs of 45 previously known lensing clusters in the SDSS DR8, and found that they are in the same range and consistent.

The colors of the newly found arcs are also in the range of those of arcs in 45 previously known lensing clusters (see the lower panel of Fig. 2).

Although the lensed arcs presented in this paper are found by visual inspection of images of hundreds of thousands galaxy clusters, our search of the arcs is efficient. The arcs we found do need following-up observations to be confirmed as lensing systems, which have to involve large optical telescopes for time-consuming spectroscopic observations. We noticed that 12 cases (including 4 almost certain, 5 probable and 3 possible cases) of 13 lensing systems in our first effort [10] have been confirmed by later spectroscopic observations [13–15]. Recently, 16 case of our second effort [11] have also been confirmed by [16]. We believe that the eight almost certain cases in our third effort, maybe together with 3 probably and 6 possible cases, can be confirmed with further spectroscopic observations.

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