Direct Evidence of a Major Merger in the Perseus Cluster

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Abstract

Although the Perseus cluster has often been regarded as an archetypical relaxed galaxy cluster, several lines of evidence including ancient, large-scale cold fronts, asymmetric plasma morphology, filamentary galaxy distribution, etc., provide a conflicting view of its dynamical state, suggesting that the cluster might have experienced a major merger. However, the absence of a clear merging companion identified to date hampers our understanding of the evolutionary track of the Perseus cluster consistent with these observational features. In this paper, through careful weak lensing analysis, we successfully identified the missing subcluster halo ($M_{200} = 1.70^{+0.73}_{-0.59} \times 10^{14} M_{\odot}$) at the > 5 σ level centered on NGC1264, which is located ~430 kpc west of the Perseus main cluster core. Moreover, a significant (>3 σ) mass bridge, which is also traced by the cluster member galaxies, is detected between the Perseus main and sub clusters, which serves as direct evidence of gravitational interaction. With idealized numerical simulations, we demonstrate that a ~3:1 off-axis major

merger can create the cold front observed ~700 kpc east of the main cluster core and generate the observed mass bridge through multiple core crossings.

Introduction

The Perseus cluster (A426; z = 0.0179) is the X-ray brightest galaxy cluster¹, exhibiting a large cooling flow centered on the brightest cluster galaxy (BCG) NGC1275², a radio mini-halo^{3,4}, and exemplary sloshing⁵⁻⁸ features. These phenomena characterize the cluster as an archetypical relaxed cluster. However, the cluster also exhibits characteristics of a dynamically young cluster: 1) its member galaxies are distributed in the east-west direction^{9,10}, 2) the plasma shows an asymmetry toward the same direction⁵, and 3) its distinct X-ray cold fronts extend to very large radii^{7,8}. These pieces of evidence observed in its baryonic components indicates that perhaps the Perseus cluster has undergone a major merger. However, the absence of a clear merging companion identified to date presents a puzzle in our understanding of its evolutionary track.

In this study, we report a discovery of the missing merging companion of the Perseus cluster based on weak-lensing (WL) analysis. In addition, we identify a significant mass bridge (> 3σ) connecting the main and sub clusters. Our idealized numerical simulations whose initial conditions are motivated by our WL results predict that a ~3:1 off-axis major merger can create the observed cold front ~700 kpc east of the main cluster core. We also find that a significant mass bridge can form from the merger and enhance its density through multiple core crossings.

We present the first WL analysis of the Perseus cluster with archival Subaru/Hyper Suprime-Cam¹¹⁻¹⁴ and Sloan Digital Sky Survey¹⁵ (SDSS) imaging data, representing the lowest (z = 0.0179) redshift galaxy cluster ever measured with WL. Although low-redshift ($z \ll 0.1$) galaxy clusters inherently suffer from low lensing efficiency, the net signal-to-noise ratio of the lensing signal per physical area at the cluster redshift is substantially enhanced by a large number of source galaxies available per physical area¹⁶. Additionally, we benefit from the high purity of a background galaxy population, as most faint galaxies in the observed field are in the background. Moreover, the noise from the large-scale structure along the line of sight is reduced due to a larger angular extent of the cluster. These advantages enable us to detect low-contrast mass structures, as long as the observational systematic errors are under control.

Results

Two-Dimensional Mass Distribution

Figure 1 shows the reconstructed mass (white) distribution around the cluster center (R < 40') based on the HSC shear catalog. The strongest convergence peak (> 9 σ) is centered at the BCG, NGC 1275 (z = 0.01756), bridged to the other peak (> 5 σ) associated with the spiral galaxy NGC 1264 (z = 0.01109) whose the line-of-sight velocity difference is ~1,800 km s⁻¹. The galaxy density peak is also in good agreement with the main halo peak, while the overall galaxy distribution stretches along the east-west direction^{9,10}, aligning with the significant (>3 σ) mass bridge indicating gravitational interaction in the past. We found that the current public XMM-Newton and Chandra data suggest no significant excess in X-ray emission at the second mass peak. With the spectroscopic catalog¹⁷ of the Perseus field, we confirmed that there is no background galaxy overdensity associated with the second mass peak.

Parametric Mass Estimation

Figure 2 presents a reduced tangential shear profile out to the cluster virial radius measured from a joint analysis of the HSC and SDSS data. The profile is centered at the BCG, and the data points within the central 5' (~110 kpc) radius are discarded. To estimate the cluster mass, we employ two kinds of halo density profiles: a Navarro-Frenk-White^{18,19} (NFW) profile and a singular isothermal sphere (SIS) profile. In the case of the mass bridge, we assume a cylindrical geometry $\kappa(h) = \kappa_0/[1 + (h/h_c)^2]^{<16>}$, where κ_0 and h_c are the central density and the characteristic width, respectively. We summarize our best-fit results of the cluster mass in Supplementary Table 1.

We estimate the virial mass of the cluster to be $M_{200} = 6.82 \pm 1.76 \times 10^{14} M_{\odot}$ assuming a single NFW halo profile with a concentration-mass (*c*-*M*) relation²⁰. This result shows excellent agreement with the mass obtained in the X-ray study²¹ ($M_{200,X-ray} = 6.65 \times 10^{14} M_{\odot}$). The SIS fit predicts a velocity dispersion of $\sigma_{WL} = 808 \pm 53 \ km \ s^{-1}$, which is slightly lower than the direct (spectroscopic) measurement of $\sigma_{v} \sim 1,000 \ km \ s^{-110,17,22,23}$. We further explore the *c*-*M* parameter space by conducting Markov Chain Monte Carlo (MCMC) analysis using a single NFW profile^{24,25}. We set a flat prior for the concentration (mass) parameter ranging from *c*=0 ($M_{200} = 1 \times 10^{12} \ M_{\odot}$) to 30 ($1 \times 10^{16} \ M_{\odot}$). The marginalized posterior distributions yield a mass of $M_{200} = 2.89^{+1.95}_{-0.98} \times 10^{14} \ M_{\odot}$ and a concentration parameter of *c* = $10.61^{+7.84}_{-4.62}$. Although the concentration is not tightly constrained, there is a hint of a steep rise of the tangential shear at the cluster core (5' < *R* < 10'). The high number density of the member galaxies in the Perseus cluster compared to other clusters^{10,26} supports this finding if we assume that galaxies Poisson-sample the dark matter.

The substructures in the reconstructed mass map (Figure 1) motivate modeling the Perseus cluster with two subhalos. We estimate the masses of these substructures by simultaneously fitting

two NFW halo density profiles^{24,25,27}. We fix each halo at the location of the associated brightest galaxy. We report that the masses of the main and sub halos are $M_{200} = 5.85^{+1.30}_{-1.18} \times 10^{14} M_{\odot}$ $(2.22^{+0.80}_{-0.58} \times 10^{14} M_{\odot})$ and $M_{200} = 1.70^{+0.73}_{-0.59} \times 10^{14} M_{\odot}$ ($0.80^{+0.36}_{-0.25} \times 10^{14} M_{\odot}$), respectively, with (without) the *c*-*M* relation. The mass ratio is approximately 3:1 for both cases.

Non-parametric Mass Estimation

Because a somewhat large difference is found between the Perseus masses with and without the c-M relation, it is important to compare the results with those obtained from non-parametric approaches. Here we choose to estimate the non-parametric mass of the Perseus cluster using the aperture mass densitometry (AMD) with the following integral^{28,29}:

$$\zeta_c(r_1, r_2, r_{max}) = \bar{\kappa}(r \le r_1) - \bar{\kappa}(r_2 < r \le r_{max}) = 2\int_{r_1}^{r_2} \frac{\langle \gamma_T \rangle}{r} dr + \frac{2}{1 - r_2^2 / r_{max}^2} \int_{r_2}^{r_{max}} \frac{\langle \gamma_T \rangle}{r} dr,$$
(1)

where $\langle \gamma_T \rangle$ is the azimuthally averaged tangential shear, r_1 is the aperture radius, and r_2 and r_{max} are the inner- and the outer-radii of the annulus. We estimate the density contrast between the inner $(r < r_1)$ and outer $(r_2 < r < r_{max})$ regions. For the control annulus, we choose $r_2 = 35'$ (760 kpc) and $r_{max} = 40'$ (870 kpc) where the predicted density within the annulus is $\bar{\kappa} = 0.0043$ from the single NFW halo fitting with the *c-M* relation. We update the convergence (κ) iteratively to determine the aperture mass as our input shear is the reduced shear. The SDSS shear catalog is not utilized since the statistical error dominates the result at large radii. Instead, we extrapolate the profile using the HSC catalog to R_{200} and obtain the projected mass of $8.55 \pm 1.16 \times 10^{14} M_{\odot}$.

Figure 3 shows the AMD result compared with the best-fit single NFW models based on different assumptions regarding the c-M relation. The projected mass profile of the AMD is consistent with the NFW aperture mass constrained by the c-M relation.

Mass bridge

In the presence of the mass bridge, we estimate masses of the bridge and the substructures by simultaneously fitting a cylindrical bridge model having a length of 430 kpc and a characteristic width of 1 Mpc between the two NFW halo profiles using the MCMC analysis. We fix the center of the profiles at each brightest galaxy and assume the *c*-*M* relation. We obtain a bridge's mass density of $\rho \sim 702\rho_{bkg}$ in units of the background density at the Perseus redshift, which is unusually high to be considered as a cosmic filament^{30,31} embedded in the plane of the sky. As the bridge density is sensitive to its inclination angle³², the provided density should be treated as an upper limit. With the inclusion of the mass bridge in our fitting, the main (sub) halo mass is estimated to be $M_{200} = 6.36^{+2.93}_{-2.38} \times 10^{14} M_{\odot} (1.68^{+1.09}_{-0.76} \times 10^{14} M_{\odot})$. The linear mass density of the mass bridge is estimated to be $\sim 10^{14} M_{\odot}$ Mpc⁻¹.

Interpretation

A mass bridge can arise from dynamical friction when two clusters pass through each other, as is often found in numerical simulations and observations³³. With the current WL masses and the timing argument³⁴, we estimate the initial infall velocity to be ~1,300 km s⁻¹ when the separation between the two halos is 2 Mpc. If the merger is head-on in the plane of the sky, the time since collision at the current observed epoch is less than 0.3 Gyrs. This recent merger scenario seems unlikely because the severely disturbed core cannot be restored to the current near-equilibrium state observed in the central region (<60 kpc)³⁵ within such a short time scale. To reconcile the features at the Perseus core and the large cold front observed ~700 kpc east, Bellomi et al.³⁶ suggest a 1:5 major merger with a large impact parameter. According to this scenario, the

large eastern cold front is 6 to 8.5 Gyrs old, and the subcluster has completely merged into the main cluster.

We carried out idealized magneto-hydrodynamic simulations of the Perseus cluster in a similar fashion, but with our WL masses (see Method for details). We find that a ~3:1 off-axis merger can reproduce the large eastern cold front and the mass bridge at the third apocenter, which is ~5.5 Gyr after the first core crossing (Figure 4). Unlike the result of Bellomi et al.³⁶, the subcluster is still intact ~400 kpc west of the main cluster core. The density of the mass bridge increases with time (Figure 4). The expected linear mass density of the bridge is ~10¹⁴ M_{\odot} Mpc⁻¹ at the third apocenter, which is roughly consistent with the current measurement (~10¹⁴ M_{\odot} Mpc⁻¹).

Although the cold fronts in the Perseus cluster have long been believed to originate from cluster collisions, no merging companion has been identified to date. This limitation leads us to a scenario wherein the responsible subcluster has already merged with the main cluster³⁶. The discovery of the subcluster and mass bridge by WL not only provides direct evidence that the Perseus cluster has undergone a major merger but also allows us to constrain the merging scenario in detail.

One of the critical questions on the cold front study is how these features have maintained their characteristic density structure over cosmic timescales. Leading theories^{37,38} suggest that magnetic fields play an essential role in preserving the structures. Consequently, detailed studies of cold fronts have the potential to infer the strength of the cosmic magnetic field through careful numerical simulations^{8,36}. The improved understanding of the merging history of the Perseus cluster enabled by the current study contributes to such efforts by providing context for interpreting the observational data and refining theoretical models.

Methods

Data Reduction

The Perseus cluster was observed with the Subaru/HSC with *g*, *r*, and *i* filters in 2014. Supplementary Table 2 summarizes the archival data that we retrieved from the SMOKA portal (https://smoka.nao.ac.jp/). We performed the low-level CCD processing (i.e., dark, overscan subtraction, flat fielding and etc.) with the the Rubin Telescope Legacy Survey of Space Time (LSST) software stack³⁹ v22_0_0 and updated the astrometric header information to the TPV format using the sip_to_pv (https://github.com/stargaser/sip_tpv.git) script⁴⁰. We created mosaic science and weight images for each filter using the calibrated frames with the SWARP package⁴¹ (http://www.astromatic.net/software/swarp). For the object detection and photometry, we ran SExtractor⁴² (https://github.com/astromatic/sextractor) with the dual image mode on the *gri* combined detection image across the given filters. The photometric calibration is performed relative to the SDSS DR16 catalog⁴³ with the cross-matched objects in the same field. Readers are referred to Finner et al.⁴⁴ and HyeongHan et al.⁴⁵ for more details.

We encapsulated time- and spatial-dependent point-spread function (PSF) by performing a principal component analysis (PCA) of the observed stars for each resampled frame^{46,47}. We reconstructed 2D PSF models by stacking the interpolated PSF image at the location of source galaxies for all associated resampled frames^{16,27,45}. As a measure of remaining systematics arising from the imperfect PSF modeling, we calculated the auto- and cross-correlation functions of the PSF residual (observed star ellipticity - model PSF ellipticity). The amplitudes are below 10^{-6} on angular scale greater than 1' for *gri* images, indicating a negligible effect on our analysis.

The Sloan Digital Sky Survey¹⁵ (SDSS) is a large (8000 sq. degree), multi-band⁴⁸ (*ugriz*) imaging and spectroscopic survey conducted by a 2.5-m telescope at Apache Point Observatory.

The Perseus cluster was observed in 2003 and 2005 in a drift-scan mode⁴⁹. We retrieved astrometrically⁵⁰ and photometrically^{51,52} calibrated science frames within 3×3 sq. degree field of view centered at NGC 1275 from the Science Archive Server (SAS; https://data.sdss.org/sas/). We generated mosaic images (Supplementary Figure 1) and detected sources for *gri* filters as of the Subaru/HSC imaging data.

We retrieved PSF metadata files from the SAS that were constructed by the PCA analysis to capture the PSF variation in temporal and spatial domain^{53,54}. We generated PSF models for each calibrated frame at a desired location so that we obtained the final PSF models as in the HSC data analysis. The residual correlation functions show the amplitude below 10^{-5} on angular scale greater than 1' for *gri* images.

Shear Measurement

For both HSC and SDSS data, we measure the shape of source galaxies with a forward modeling approach^{16,27,45}. In this study, we fit the PSF-convolved elliptical Gaussian model $[M_{j,k}(x,y)]$ to the observed postage image $[O_{j,k}(x,y)]$ across three different filters (i.e., *gri*) simultaneously⁵⁵:

$$\chi^{2} = \sum_{j=1}^{n} \sum_{k}^{g,r,i} \frac{\left[o_{j,k}(x,y) - M_{j,k}(x,y)\right]^{2}}{\sigma_{j,k}^{2}},$$
(2)

where $\sigma_{j,k}$ is an root mean square (rms) postage image. For neighboring objects, we assign 10^{10} to the rms value based on the segmentation map obtained from the SExtractor. The minimization is performed by using the MPFIT module⁵⁶ with three global variables (i.e., ellipticity, semi-minor axis, and position angle), one local variable (amplitude) while fixing galaxy position, noise, and background level.

We select background source galaxies using photometry and shape information. For the HSC data, the objects having magnitudes between 23 < r < 26 are chosen without a color cut since the member galaxy and foreground contamination is negligible in the selected magnitude range thanks to the cluster's proximity¹⁶. We apply size criteria that the half-light radius in *i* band is greater than 0". 4 to avoid stellar confusion and the semi-minor axis is larger than 0.4 pixel to remove artifacts due to pixellation (see Figure 14 in Jee et al.⁵⁷). We additionally impose the criteria of STATUS = 1 from MPFIT and the ellipticity error less than 0.3 to secure a stable fitting result. We achieve a source density of 23 arcmin⁻² or 47,479 Mpc⁻².

For the SDSS data, we choose objects magnitudes between 18 < r < 23 because of the shallow imaging depth. To minimize the member galaxy and stellar contamination, we select objects having *i* band half-light radius between 1" and 2".4. Additionally, we impose the ellipticity error cut <0.4, the semi-minor axis cut >0.6 pixel, and the STATUS=1 requirement. The final source density for the SDSS imaging data is 0.6 arcmin⁻² or 1,350 Mpc⁻².

In the absence of redshift information for each source galaxy, we estimate the source redshift using a photometric redshift as a reference catalog. We apply the magnitude constraint to the COSMOS2020 catalog⁵⁸ and weight the number density in each magnitude bin to match the source catalog to account for the difference in the imaging depth. The lensing efficiency is $\langle \beta \rangle = 0.95$ (corresponding effective redshift is $z_{eff} = 0.43$) and the width of the distribution is $\langle \beta^2 \rangle = 0.92$. We correct the reduced shear, $g = \gamma/(1 - \kappa)$ where γ is the shear and κ is the convergence, in a first order to account for the redshift distribution of the sources⁵⁹: $g' = [1 + \kappa(\langle \beta^2 \rangle / \langle \beta \rangle^2 - 1)]g$.

The Perseus cluster $(b \sim -13^{\circ})$ is located near the Galactic plane where the dilution effect by stellar contamination can be as high as 5%^{60,61}. Accounting for this effect, we apply the multiplicative bias correction $m = 1.1^{60}$ to the HSC shear catalog.

Idealized Simulation Setup

We run idealized magneto-hydrodynamical cluster merger simulations using a GPUaccelerated Adaptive Mesh Refinement code, GAMER- 2^{62} , to investigate the dark matter distribution of the halos and bridge. We set a fixed number of cells (8³) for each "patch" in a 15 Mpc-side box that allows us to achieve a spatial resolution of ~15 kpc at the cluster center and ~200 kpc in the outskirts.

We place two dark matter halos at a separation of 3 Mpc. Each halo follows an NFW profile whose initial dark matter distribution is generated by the cluster_generator package (https://github.com/jzuhone/cluster_generator). The main halo has a total mass of $5.8 \times 10^{14} M_{\odot}$ with a concentration parameter of c = 3.8 and a baryon fraction of 0.13 at R_{200} . The distribution of intracluster medium (ICM) follows the modified beta model suggested by Vikhlinin et al.⁶³ hosting a cool core. The subhalo has a total mass of $1.7 \times 10^{14} M_{\odot}$ and a concentration of c =4.2. We set a turbulent intracluster magnetic field with the average plasma beta=100. Its initial infall velocity is 1,200 km s⁻¹ toward the main halo with an impact parameter of 1.8 Mpc. Readers are referred to Brzycki & ZuHone⁶⁴ and Lee et al.⁶⁵ for more details.

Data Availability: The raw Subaru/HSC and SDSS imaging data used for the current study are publicly available. The processed mosaic images and data points in the article figures are available on request from the authors.

Code Availability: Our custom data processing codes are available on request from the authors.

Acknowledgements:

Author contributions

Competing interests



Figure 1: Dark matter and galaxy distribution of the Perseus cluster. The RGB color image consists of blue, green, and red channels represented by intensities in the Subaru/HSC g, r, and i-band images, respectively. White contours indicate a significance (κ/σ_{κ}) of the reconstructed mass that starts from 3σ with 1σ step each. We reconstructed a convergence (κ) map by using the Fourier-inversion method⁶⁶ and obtained its noise (σ_{κ}) map by generating 1000 convergence fields from the resampled HSC shear catalogs. The circle in the lower right corner represents the effective

mass reconstruction smoothing scale $\sigma = 165''$. We obtained consistent results with other mass reconstruction algorithms^{67,68}. Orange (green) contours show the smoothed number (luminosity) distribution of spectroscopically confirmed member galaxies identified in Kang et al.¹⁷. The red solid line indicates the location of the large cold front ~700 kpc east^{7,8}. Throughout the paper, we assume a flat Λ CDM cosmology characterized by h = 0.7 and $\Omega_{m,0} = 1 - \Omega_{\Lambda,0} = 0.3$.



Figure 2: Reduced shear profile of the Perseus cluster using the HSC-SDSS merged shear catalog. Top: Azimuthally averaged tangential shear profile with respect to the BCG. Each error bar indicates 1σ confidence level that accounts for the ellipticity dispersion and measurement error. Green dashed lines represent the R_{500} and R_{200} adopted from Simionescue et al.²¹. Dashed lines are the best-fit models with different assumptions. Readers are referred to the main text for more details. Bottom: Cross shear signal obtained by rotating galaxy position angles by 45°. The cross shear is consistent with the null signal.



Figure 3: Projected mass profiles comparing parametric (analytic projection of NFW profiles) results with nonparametric (aperture mass densitometry) ones. The red (blue) dotted line shows an analytic projection of the NFW profile with (without) the *c*-*M* relation. The green solid line represents the aperture mass densitometry while the results outside 35' (~760 kpc) are extrapolated. The black solid line indicates the aperture mass of the SIS profile. Shaded regions indicate 1σ statistical uncertainties.



Figure 4: Numerical simulation of the hypothesized merger in the Perseus cluster. Left: Snapshot of the dark matter density contours (white) overlaid on the Gaussian-gradient magnitude ($\sigma = 0.125$ kpc) filtered X-ray surface brightness map at ~5.5 Gyr after the first core passage. The dark matter map is smoothed with a $\sigma = 10$ kpc Gaussian kernel. The X-ray surface brightness map is produced from the 0.5-7 keV energy interval. Right: Halo separation (blue) and mass bridge density (red) evolution with time. The mass bridge linear density is measured from a 30 kpc length cylindrical volume at the center of the two halos. The vertical dashed line indicates the 3rd apocenter phase displayed in the left panel. The initial mass of the main (sub) clusters is $5.8 \times 10^{14} M_{\odot}$ ($1.7 \times 10^{14} M_{\odot}$), adopting the value from the WL mass obtained with the *c-M* relation. While we did not finetune our numerical simulation to exactly replicate the observations, the current snapshot reasonably reproduces the observed X-ray and WL features. This includes the cold front ~700 kpc east of the main core, the subcluster ~430 kpc west of the main core, and the mass bridge between the main and sub clusters.

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Supplementary Figure 1: The color composite SDSS image. The RGB color image consists of blue, green, and red channels represented by SDSS *g*, *r*, and *i*-band images, respectively. The outer yellow circle indicates the 1.5° (2.1 Mpc) radius and the inner circle (r = 40'; ~870 kpc) represents the HSC coverage.

Supplementary Table 1: Mass Estimates from best-fit models

Fitting Model	Main halo M_{200} (× 10 ¹⁴ M_{\odot})	C200	Subhalo M_{200} (× 10 ¹⁴ M_{\odot})	C 200	$\chi^2/d.o.f.$
Single-halo-fitting NFW w/ <i>c-M</i> relation (1)	$6.82^{+1.76}_{-1.76}$	$3.83^{+0.03}_{-0.01}$	N/A	N/A	0.54
Single-halo-fitting w/o <i>c-M</i> relation	$2.89^{+1.95}_{-0.98}$	$10.61^{+7.84}_{-4.62}$	N/A	N/A	0.28
Single-halo-fitting SIS (2)	$2.84^{+0.59}_{-0.52}$	N/A	N/A	N/A	0.54
Two-halo-fitting NFW w/ c-M relation (1)	$5.85^{+1.30}_{-1.18}$	$3.84^{+0.04}_{-0.02}$	$1.70^{+0.73}_{-0.59}$	$4.16^{+0.24}_{-0.11}$	0.28
Two-halo-fitting NFW w/o c-M relation	$2.22\substack{+0.80\\-0.58}$	$14.56^{+8.75}_{-4.72}$	$0.80\substack{+0.36\\-0.25}$	$14.62^{+5.11}_{-4.28}$	0.28

(1) We assume the *c*-*M* relation adopted from Ishiyama et al.²⁰. (2) We derive the mass from

the best-fit velocity dispersion, $\sigma_{\rm WL} = 808 \pm 53 \ km \ s^{-1}$.

Supplementary Table 2: Summary of HSC observations

Filter	Exposure Time (s)	Observation Date	(FWHM) (arcsec)	Limiting Magnitude (1)
HSC-g	23,850	2014	0.7	28.2
HSC-r	4,380	2014	0.6	26.5
HSC-i	2,190	2014	0.5	26.0

(1) We quote the 5σ limiting magnitude of a point source.