The puzzling merging cluster Abell 1914: new insights from the kinematics of member galaxies

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ABSTRACT

We analyse the dynamical state of Abell 1914, a merging cluster hosting a radio halo, quite unusual for its structure. Our study considers spectroscopic data for 119 galaxies obtained with the Italian Telescopio Nazionale Galileo. We select 89 cluster members from spatial and velocity distributions. We also use photometry Canada–France–Hawaii Telescope archives. We compute the mean cluster redshift, ⟨z⟩ = 0.168, and the velocity dispersion which shows a high value, σv = 1210±125 km s⁻¹. From the 2D analysis we find that Abell 1914 has a north-east (NE)–south-west (SW) elongated structure with two galaxy clumps, that mostly merge in the plane of the sky. Our best but very uncertain estimate of the velocity dispersion of the main system is σv, main ∼ 1000 km s⁻¹. We estimate a virial mass Msys = 1.4–2.6 × 10¹⁵ h⁻¹ M⊙ for the whole system. We study the merger through a simple two-body model and find that data are consistent with a bound, outgoing substructure observed just after the core crossing. By studying the 2D distribution of the red galaxies, photometrically selected, we show that Abell 1914 is contained in a rich large-scale structure, with two close companion galaxy systems, known to be at z ∼ 0.17. The system at SW supports the idea that the cluster is accreting groups from a filament aligned in the NE–SW direction, while that at NW suggests a second direction of the accretion (NW–SE). We conclude that Abell 1914 well fits among typical clusters with radio haloes. We argue that the unusual radio emission is connected to the complex cluster accretion and suggest that Abell 1914 resembles the well-known nearby merging cluster Abell 754 for its particular observed phenomenology.

Key words: galaxies: clusters: general – galaxies: clusters: individual: Abell 1914.

1 INTRODUCTION

A fraction of galaxy clusters shows the presence of diffuse radio emission on Mpc scale. In general, we can distinguish between two morphologies: ‘radio haloes’ and ‘radio relics’. In the first case, the emission comes from central cluster regions, while ‘relics’ take place in the peripheral zones (Giovaninni et al. 2002; Ferrari et al. 2008; Venturi 2011; Feretti et al. 2012). The synchrotron origin of this radio emission reveals the presence of a large-scale magnetic field and relativistic particles spread out of the cluster. Nowadays, cluster mergers seem to be the most reasonable framework proposed to provide enough energy for accelerating electrons to relativistic velocities and for magnetic field amplification. In this scenario, radio relics seem to be directly linked with merger shocks (Ensslin et al. 1998; Roettiger, Burns & Stone 1999; Ensslin & Gopal-Krishna 2001; Hoeft, Brüggen & Yepes 2004). Instead, the turbulence following cluster mergers has been proposed as one of the most important effects to produce giant radio haloes (Brunetti et al. 2001, 2009). However, the precise scenario for radio halo formation is still debated. In fact, there are two main theoretical approaches to the problem: re-acceleration versus hadronic models (Brunetti et al. 2009, and references therein).

Usually, X-ray observations are used to study the dynamical state of clusters with diffuse radio emission. Indeed, all statistical analyses are derived from X-ray data (Schuecker et al. 2001; Buote 2002; Cassano et al. 2010; Rossetti et al. 2011) and properties of radio emission are derived in general from X-ray temperature and luminosity (see e.g. Giovannini et al. 2002, and references therein). In fact, predictions based on turbulent re-acceleration models well agree with the radio observations of haloes (Cassano, Brunetti & Setti 2006). In this sense, Govoni et al. (2001) also find

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a strong correlation between X-ray and radio emission when they compare point-to-point individual surface brightnesses. In addition, Basu (2012) reveals no evidence of bimodality in the radio-power-integrated Sunyaev–Zeldovich (SZ) effect diagram while, at the contrary. Brunetti et al. (2007) find this bimodal feature in the radio-power–X-ray luminosity diagram. This fact reveals the need to manage other research ways in addition to X-ray techniques.

Optical information is an important way to investigate the dynamics of cluster mergers (Girardi & Biviano 2002). The spatial distribution and kinematics of galaxy members allow us to detect substructures and to analyse possible pre- and post-merging groups, and to distinguish between evolving mergers and remnants. Moreover, optical data are complementary to X-ray information because the intracluster medium (ICM) and galaxies react on different time-scales during a collision. This is clearly shown in numerical simulations by Roettiger, Loken & Burns (1997). Thus, for example, the importance of combining X-ray and optical data to study merging scenarios is shown by Multiwavelength Sample of Interacting Clusters (MUSIC) project (Maurogordato et al. 2011).

In this context, we are now progressing on the Dynamical Analysis of Radio Clusters (DARC; see Girardi, Barrena & Boschin 2010) project, which uses spectroscopic and photometric information of galaxy members to analyse the internal dynamics of clusters with diffuse radio emission.

We have carried out an extensive observational program focused on the cluster of galaxies Abell 1914 (hereafter A1914). A1914 is a rich cluster, X-ray luminous, hosting a hot ICM. It shows an Abell richness class $R = 2$ (Abell, Corwin & Olowin 1989), $L_X (0.1–2.4 \text{ keV}) = 17.93 \times 10^{44} \text{ erg s}^{-1}$ (Ebeling et al. 1996) and $kT_X \sim 9 \text{ keV}$ (Baldi et al. 2007; Maughan et al. 2008). Following the Bautz–Morgan classification, A1914 is a type II structure (Abell et al. 1989), while it is an ‘L-type’ (‘linear’) cluster in the Rood–Sastry morphological scheme (Struble & Rood 1987).

Dahle et al. (2002) study the mass and light distributions using weak lensing techniques. They recover the elongated shape of this cluster in the north-east (NE)–south-west (SW) direction and find that the light distribution well follows the mass profile. The two brightest cluster galaxies trace the two highest peaks in the mass distribution, although in the reverse order, i.e. the highest peak is close to the second brightest galaxy (Okabe & Uematsu 2008). On the other hand, Jones et al. (2005) analyse the galaxy distribution in the Palomar Observatory Sky Survey (POSS) digital. They find signs of dynamical activity with two distinct groups of galaxies with no single dominant galaxy.

Buote & Tsai (1996) develop the first analysis of the X-ray morphology of this cluster using ROSAT data. They find that A1914 is a relaxed structure, but Jones et al. (2005) show some evidence against this thesis, suggesting that this cluster is not so relaxed. They find no evidence for a cool core, an unusual high X-ray temperature and notice that ROSAT data are very poorly fitted using a $\beta$ model. Then, using Chandra X-ray data, Govoni et al. (2004) show clear evidence of merger. In fact, they find a clear elongation of the X-ray surface brightness (along WNW–ESE; see fig. 5d of Govoni et al. 2004). In the last years, using Chandra data, A1914 has been classified as a non-relaxed cluster (Baldi et al. 2007; Maughan et al. 2008).

Concerning the radio emission, Komissarov & Gubanov (1994) first report evidence for a diffuse and extended radio source (see also Giovannini, Tordi & Feretti 1999; Kemper & Sarazin 2001). Moreover, Bacchi et al. (2003), using Very Large Array (VLA) data, show the presence of an unpolarized halo. The halo covers a $7.4 \times 5.3 \text{ arcmin}^2$ area with a power $P_{\text{1.4 GHz}} = 8.72 \times 10^{24} \text{ W Hz}^{-1}$. Govoni et al. (2004) point out that the diffuse radio emission is quite puzzling by a bright component elongated in the NW–SE direction and a more typical low-brightness halo in the cluster centre (see fig. 5d of Govoni et al. 2004 and fig. 1 of this work). The bright radio region does not follow either the elongation of the X-ray surface brightness. This fact is quite unusual, because in the majority of clusters the elongated diffuse radio halo follows the direction of the merger (e.g. the ‘bullet’ cluster 1E0657–56, Markevitch et al. 2002; but see Abell 523, Giovannini et al. 2011).

Despite several studies based on X-ray data, published redshift data are not enough to perform the detailed dynamical study of A1914. The work we present here is based on new spectroscopic data obtained with the Telescopio Nazionale Galileo (TNG). We also use photometric data from the Canada–France–Hawaii Telescope (CFHT) archive.

This paper is organized as follows. We present optical data, including redshifts and photometry information, in Section 2. We expose our results on the cluster structure in Section 3. The discussion on the dynamical state of A1914 and conclusions are presented in Sections 4 and 5, respectively.

Unless otherwise stated, we present errors at the 68 per cent confidence level (hereafter c.l.). Along this paper, we work using $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $h_{70} = H_0/(70 \text{ km s}^{-1} \text{ Mpc}^{-1})$ and a flat cosmology with $\Omega_0 = 0.3$ and $\Omega_\Lambda = 0.7$. Within this cosmology, 1 arcmin corresponds to $\sim 172 h_{70}^{-1} \text{ kpc}$ at the cluster redshift.

2 THE DATA SAMPLE

2.1 Spectroscopic data

We performed observations of A1914 using Device Optimized for the Low Resolution (DOLORES) multi-object spectrograph at the TNG telescope in 2010 March. We used the LR-B grism, which provides a dispersion of 187 Å mm$^{-1}$. DOLORES works with a 2048 × 2048 pixels E2V CCD. The pixel size is 13.5 µm. We retrieved a total of four multi-object spectroscopy (MOS) masks containing 146 slits. We exposed 3600 s for each mask.

Spectra were reduced using standard IRAF tasks. Radial velocities were computed by using the cross-correlation technique (Tonry & Davis 1979) with the IRAF/NCSSAO task, as we have proceeded with other clusters already analysed in the DARC project (for a detailed description, see e.g. Boschin et al. 2012). In six cases (IDs 78, 79, 83, 99, 100, 107 and 112; see Table 1), we considered the IRAF/EMSAO redshift (based on the wavelength of emission lines in the spectra) to get a realistic estimation. So, our catalogue lists 113 galaxy redshifts in the field of A1914. We also considered six redshifts more from the Sloan Digital Sky Survey (SDSS) archive (IDs from 114 to 119; see Table 1).

The true intrinsic errors are larger than those formal errors given by the cross-correlation (e.g. Malumuth et al. 1992; Bardelli et al. 1994; Ellingson & Yee 1994; Quintana, Carrasco & Reisenegger 2000). To correct this effect, some galaxies were observed in more than one mask. This allows us to estimate the intrinsic errors in data

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1 See also http://adlibitum.oat.ts.astro.it/girardi/darc, the website of the DARC project.

2 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
of the same quality acquired with the same instrumentation. Our spectroscopic survey provides duplicate estimations for 18 galaxies. So, following the method detailed in Barrena et al. (2009) for these galaxies and using the weighted mean of the two measurements,
we concluded that true intrinsic errors are larger than formal cross-correlation ones by a factor of 2. For the redshifts estimated with the EMSAO task we considered the largest value between 100 km s\(^{-1}\) and the formal error.

We also considered nine galaxies having redshift in the SDSS and lying in the same field spanned by our spectroscopic data. Three of these SDSS targets were also observed with the TNG/DOLORES. We find no systematic deviations between the SDSS and our redshifts. We add the remaining six galaxies to our TNG catalogue. Finally, we obtain a spectroscopic catalogue of 119 galaxies, with a median value of the \(c\varepsilon\) errors of 74 km s\(^{-1}\).

\section*{2.2 Photometry and galaxy catalogue}

We also use public photometric data obtained with Megaprime/Megacam at the CFHT. In particular, we consider \(r^{\text{Mega}}\) and \(g^{\text{Mega}}\) band\(^3\) images retrieved from the Canadian Astronomy Data Centre (CADC) Megapipe archive (Gwyn 2009). These images cover an area of 1.05 \(\times\) 1.16 deg\(^2\) with a depth of \(g^{\text{Mega}} = 27.2\) and \(r^{\text{Mega}} = 26.8\) limiting magnitudes (at the 5\(\sigma\) detection level). Megaprime photometry is 90 per cent complete down to \(g^{\text{Mega}} = 24.8\) and \(r^{\text{Mega}} = 24.6\). We corrected \(g^{\text{Mega}}\) and \(r^{\text{Mega}}\) CFHT magnitudes for galactic extinction assuming extinction values obtained from SDSS Data Release 7 (DR7) in the central cluster region.

Table 1 lists our velocity catalogue and photometry (see also Fig. 2). We present an identification (ID) number in column 1 (galaxy members are listed in italic format); right ascension and declination (J2000) in column 2; CFHT \(p^{\text{Mega}}\) magnitudes in column 3 and heliocentric radial velocities \(v = c\varepsilon\) and errors \(\Delta v\) in columns 4 and 5, respectively.

Our spectroscopic sample is 80 per cent (50 per cent) complete down to \(r = 18.3\) (=19.7), within an elongated region of 60 arcmin\(^2\) (corresponding to an area of 1.1 \(\times\) 1.6 Mpc at the redshift of the cluster) around the cluster centre. The brightest cluster galaxy is ID 29 (\(p^{\text{Mega}} = 15.87\), hereafter BCG1). It lies at the SW and is non-dominant (in luminosity) in the cluster. In fact, there is a second brightest cluster galaxy at the NE (ID 20, \(p^{\text{Mega}} = 16.39\), hereafter BCG2). The two galaxies are separated by \(\sim 1.7\) arcmin, i.e. \(\sim 0.3\) \(h_\text{100}^{-1}\) Mpc at the cluster distance.

\section*{3 ANALYSIS OF THE OPTICAL DATA}

\subsection*{3.1 Cluster member selection}

In order to select cluster members we followed a procedure with two steps. First, we ran the 1D adaptive-kernel method (hereafter 1D-DEDICA; Pisani 1993, 1996; see also Fadda et al. 1996; Girardi et al. 1996). We detected significant peaks (at \(>99\) per cent c.l.) in the velocity distribution. This procedure found A1914 as a peak at \(z \sim 0.1675\), containing 100 (provisional) cluster candidates (in the range 45 \(921 \leq v \leq 58 \, 839\) km s\(^{-1}\), see Fig. 3). We also found 18 and one background and foreground galaxies, respectively.

Then, in a second step, we only consider the 100 likely cluster candidates to run the ‘shifting gapper’ method proposed by Fadda et al. (1996; see also e.g. Girardi et al. 2011), which takes into account a combination of velocity and position of the galaxies. This method needs the definition of a cluster centre, but the optical centre of A1914 is not obvious due to the absence of a clear dominant galaxy and to the offset of the X-ray centre (e.g. Maughan et al. 2008). So, we decided to assume as cluster centre the position of BCG1 (see Table 1). The application of the ‘shifting gapper’ rejected another eleven galaxies leading to a final sample of 89 cluster members (Fig. 4, top panel).

In order to check the robustness in the galaxy member selection and estimate how the choice of cluster centre could affect this selection, we executed the shifting gapper method, but now considering the BCG2 as cluster centre. This procedure selected identical galaxy members. That is, in our case, the galaxy member selection, and so the dynamical analysis here exposed is not affected by the choice of the cluster centre. So, we decided to consider the BCG1 as cluster centre, as in agreement with Okabe & Umetsu (2008).

\subsection*{3.2 Global cluster properties}

By using the biweight method (Beers, Flynn & Gebhardt 1990, \textsc{rostat} software) with the 89 cluster members, we obtained a mean cluster redshift of \((z) = 0.1678 \pm 0.0004\), i.e. \((v) = (50\,313 \pm 140)\) km s\(^{-1}\). In addition, by applying the same method and correcting for cosmological effects and standard velocity errors (Danese, De Zotti & di Tullio 1980), we obtained \(\sigma_v = 1210_{-110}^{+120}\) km s\(^{-1}\) (errors were estimated using the bootstrap technique). However, in order to check the robustness of this estimate, we study the variation of \(\sigma_v\) with the distance to the cluster centre (Fig. 4, bottom panel). The integral \(\sigma_v\) profile is flat, suggesting that the estimation of \(\sigma_v\) is robust. Furthermore, when considering members within \(0.1\,h_\text{100}^{-1}\) Mpc from the BCGs (that is two groups of seven and eight galaxy members around BCG1 and BCG2, respectively), we measure similar mean velocities. We only find a modest difference, being \((\dot{v})_{\text{BCG2}} < (\dot{v})_{\text{BCG1}}\), which is in agreement with the finding that \(v_{\text{BCG2}} < v_{\text{BCG1}}\) (see also Section 3.5).

\subsection*{3.3 The small high-velocity group}

Fig. 4 (top panel) shows that most of the interlopers have a very similar high velocity. We assign eight galaxies to a likely galaxy group (red squares in Fig. 4, top panel). Seven out of these eight galaxies lie in the SW cluster region, thus reinforcing the idea that this is a real structure. For this high velocity galaxy group (HVG) we estimate \((\dot{v})_{\text{HVG}} = (55\,557 \pm 89)\) km s\(^{-1}\) and \(\sigma_{v,\text{HVG}} = 221_{-46}^{+55}\) km s\(^{-1}\).

\subsection*{3.4 Velocity distribution and 3D substructure}

Deviations from Gaussianity in the velocity distribution are interpreted as an important sign that clusters present a complex dynamics (Ribeiro, Lopes & Trevisan 2011).

In order to check the Gaussianity in the velocity distribution, we used three profile estimators. These are the skewness, the kurtosis and the scaled tail index (STI; see Bird & Beers 1993). The STI finds evidence for non-Gaussianity at about 95–99 per cent c.l., suggesting a heavy tailed distribution (see Bird & Beers 1993, and their table 2).

Furthermore, we investigated the presence of gaps in the velocity distribution. By using the weighted gap analysis presented by Beers et al. (1991, 1992, \textsc{rostat} software), we detect one significant gap at the 97 per cent c.l. This gap divides A1914 into two groups, composed of nine and 80 galaxies at low and high velocities, respectively. By applying the 2D Kolmogorov–Smirnov test (Fasano

\footnote{See the URL http://www2.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/megapipe/docs/proc.html#photocal for a comparison between Megacam and SDSS filters.}
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Figure 1. Multiwavelength image of the central region of A1914. The grey-scale image in background corresponds to the optical $M_{\text{eg}}$-band (CFHT archive). Superimposed, with orange and yellow colours, we also show the smoothed X-ray image in the 0.3–7 keV energy range (Chandra archive). Contour levels represent the VLA radio image at 1.4 GHz (courtesy of F. Govoni; see Bacchi et al. 2003). Green circle and square mark the centres of the density peaks detected in our analysis of the galaxy distribution (see Section 3.6). Blue ‘X’ marks the centroid of the X-ray surface brightness (Govoni et al. 2004). Labels indicate the positions of the two brightest cluster galaxies (BCG1 and BCG2; see Section 2.2 and Table 1). North is up and east is left.

& Franceschini 1987) we see that the galaxies of the two groups present the same spatial distribution (see Fig. 5).

We also applied the 1D Kaye’s mixture model (Ashman, Bird & Zepf 1994; see also e.g. Boschin et al. 2012) – hereafter 1D-KMM – to search for bimodal partitions significantly fitting to the velocity distribution. The most likely solution (well under the 90 per cent significance c.l.) indicates two groups of 15 and 74 galaxies, spatially not differing. Considering the KMM results, which take into account the group membership probability, we obtain that the two groups differ for about $\sim 140$ km s$^{-1}$ in the cluster rest frame ($\langle v \rangle_{\text{KMM1D-LV}} = 50\,155$ km s$^{-1}$ and $\langle v \rangle_{\text{KMM1D-HV}} = 50\,319$ km s$^{-1}$) and the high-velocity group has a much higher velocity dispersion ($\sigma_{v,\text{KMM1D-HV}} \sim 980$ km s$^{-1}$ versus $\sigma_{v,\text{KMM2D-LV}} \sim 330$ km s$^{-1}$).

Correlations between spatial and velocity distributions of cluster galaxies usually indicate the presence of actual substructures. With this idea in mind, we used several techniques to reveal the structure of A1914 by combining positions and velocities. First, we searched for velocity gradients in the plane of the sky by performing multiple linear fits. Fig. 6 shows the results of this test which reveal no evidence of gradients. In addition, we performed a set of
3D tests: the classical $\Delta$ statistics (Dressler & Schechter 1988), as well as its variation which considers separately mean velocity and velocity dispersion kinematical indicators (Girardi et al. 1997; Ferrari et al. 2003); the $\alpha$-test (West & Bothun 1990) and the $\epsilon$-test (Bird 1994) based on the projected mass predictions. None of the above-mentioned tests yielded positive detection of substructures. Moreover, we found no substructure by applying the technique developed by Serna & Gerbal (1996), also named the ‘Htree method’ (see also Durret, Laganá & Bertin 2010; Boschin et al. 2012).

3.5 2D galaxy distribution of the spectroscopic catalogue

We applied the 2D adaptive-kernel technique (hereafter 2D-DEDICA) to the spatial distribution of member galaxies. This method found only one significant peak, lying close to BCG2 and elongated towards BCG1. Fig. 7 shows that A1914 presents an elongated profile in the NE–SW direction, suggesting a bimodal structure. To further investigate this point we applied the 2D-KMM method using as seeds the cluster members contained within 0.1 $h^{-1}_{70}$ Mpc from BCG1 and BCG2 (seven and eight galaxies, respectively). The method detects a bimodal solution, significant at the 99.6 per cent c.l., with the KMM2D-SW group of 65 galaxies at SW and the KMM2D-NE group of 24 galaxies at NE (but note that both BCG1 and BCG2 are now both assigned to the SW group). When applying the 3D-KMM method we still found a bimodal solution with two groups of 69 (SW) and 20 galaxies (NE), with BCG1 and BCG2 assigned to the SW and NE groups, respectively. However, the significance of the 3D result
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Figure 3. Redshift galaxy distribution. Solid line shows the histogram corresponding to the 100 (provisional) galaxies assigned to A1914 by the 1D-DEDICA reconstruction method.

Figure 4. Top panel: rest-frame velocity versus projected distance (BCG1 is assumed as the cluster centre) for the all 100 galaxies within the velocity peak. Large green circles correspond to the location of the two brightest cluster galaxies. Cyan crosses show galaxies rejected as interlopers with the ‘shifting gapper’ method. Galaxies belonging the HVG group are indicated with red squares. Middle panel: differential (blue circles) and integral (black dots) profiles of mean velocity for the 89 cluster members. We compute differential values within five annuli, each of $\sim0.2\,h_{70}^{-1}\text{Mpc}$, from the cluster centre. The integral profiles consider mean velocities of all galaxies within a given distance. The first value is obtained from the five inner galaxy members. Error bars show uncertainties at 68 per cent c.l. The band within red lines indicates the integral mean velocity when using BCG2 as the cluster centre. Bottom panel: the same as middle panel but for the $\sigma_V$ profiles. The horizontal line represents the value for the X-ray temperature (9 keV) transformed into $\sigma_V$ assuming a $\beta_{spec} = 1$ model for the density-energy distribution between ICM and galaxies (see Section 4).

Figure 5. Upper panel: velocity distribution of the galaxy members (black line) and to the HVG (red line). Velocities of BCG1 and BCG2 are also indicated by arrows. Lower panel: streak density diagram of cluster members (black) and HVG members (red). The significant gap in the velocity distribution is indicated by an arrow.

Figure 6. Projected spatial distribution of 89 cluster members (open symbols) and the eight members of HVG (red solid circles). The size of symbols is directly correlated with the value of the radial velocity for each galaxy. Circles and squares indicate the two groups at low and high velocities, as detected through the weighted gap analysis. The plot is centred on the BCG1 position.

is only at the 96 per cent c.l., thus indicating that velocities do not give a positive contribution to the separation of the two substructures. In fact, according to the Kolmogorov–Smirnov test, there is no difference between the velocity distributions of the two 3D groups.
3.6 2D galaxy distribution of the photometric catalogues

Our spectroscopic sample does not map the whole cluster field, besides of suffering for magnitude incompleteness. To overcome these restrictions we resorted to the photometric catalogues. Using the CFHT photometry, we construct \((g' - r')\) versus \(r'\) diagram for galaxies with available spectroscopy. Black and red squares indicate member and non-member galaxies. The solid line gives the CMR determined on member galaxies; the dashed lines are drawn at \(\pm 0.2\) mag from this value.

In addition, using CFHT data we found an important secondary peak lying at SW of BCG1. In the \(r' < 21\) sample, the two peaks are separated by \(\sim 2.5\) arcmin, i.e. \(\sim 0.4\) \(h^{-1}\) Mpc at the cluster distance.

We also note that the external regions of A1914 are particularly rich of structures. Fig. 9 shows the position of four galaxy clusters listed by NASA/IPAC Extragalactic Database (NED): 1. NSCS J142452+373753 at \(z \sim 0.17\) (identified in the Digitized Second Palomar Observatory Sky Survey (DPOSS); Lopes et al. 2004; and then in SDSS); 2. 400d J1425+3758 at \(z \sim 0.17\) (identified in the 400 Square Degree ROSAT PSPC Galaxy Cluster Survey; Burenin et al. 2007); 3. NSCS J142638+375327 at \(z \sim 0.20\); 4. GMBCG J216.49530+37.62102 at \(z \sim 0.23\) (identified in the SDSS DR7; Hao, McKay & Koester 2010). When using the best sample (the one with \(r_{\text{Mega}} < 21\)), the two clusters closest in redshift (N.1 and N.2) are well detected, while the clusters N.3 and N.4 are better detected in the deeper magnitude ranges, thus confirming us that we are including more and more interlopers among our likely cluster members when considering fainter galaxies.

Table 2 lists information for the four highest, significant peaks in the galaxy distribution using the CFHT data: the estimated number of likely members, \(N_S\) (column 2); equatorial coordinates of the substructure (column 3); the relative isodensity respect the highest peak, \(\rho_S\) (column 4); the \(\chi^2\) for each clump (column 5). Galaxy clusters No. 1 and No. 4 are detected as significant peaks in the \(21 \leq r_{\text{Mega}} < 22\) sample, too, but having lower density.

4 DISCUSSION

We estimate a high value of the velocity dispersion, \(\sigma_V = 1210^{+125}_{-110} \text{ km s}^{-1}\). This result well agrees with a hot ICM showing a mean \(T_X \sim 9\) keV (Baldi et al. 2007; Maughan et al. 2008) when assuming energy equipartition between galaxies and gas.
energy per unit mass, \( \beta_{\text{spec}} = 1 \), both suggesting a massive galaxy cluster. In the following sections we discuss our findings on the dynamical mass and cluster structure. Thus, based on these results, we propose a two-body model and time-scale for the collision of substructures in Abell 1914.

### 4.1 Mass estimates

We computed the global virial quantities assuming the dynamical equilibrium (but see in the following) and in the framework of usual assumptions, i.e. cluster sphericity and coincidence in the galaxy-mass distributions. Following the method detailed in Girardi & Mezzetti (2001, see also Girardi et al. 1998) we obtained \( R_{\text{vir}} \), an estimation of \( R_{\text{SIS}} \), and the mass within this radius. We assume a quasi-virialized region of \( R_{\text{vir}} = 0.17 \sigma_v / H(z) h_70^{-1} \) Mpc (see equation 1 of Girardi & Mezzetti 2001, with the corresponding scaling of \( H(z) \) from equation 8 of Carlberg, Yee & Ellingson 1997, for \( R_{\text{SIS}} \)). We estimate the mass using the equation \( M = M_{\text{vir}} - \text{SPT} = 3\pi/2 \sigma_v^2 R_{\text{vir}} / G - \text{SPT} \) (equation 3 of Girardi & Mezzetti 2001), with \( R_{\text{vir}} \) computed as described in equation (13) of Girardi et al. (1998), with \( A = R_{\text{SIS}} \) as a close approach, and being the surface pressure term (SPT) correction a 20 per cent of \( M_{\text{vir}} \).

Both \( R_{\text{vir}} \) and \( M \) were estimated considering the velocity dispersion with the usual scaling laws, where \( R_{\text{vir}} \propto \sigma_v \) and \( M(< R_{\text{vir}}) \propto \sigma_v^2 \). We obtained \( M(< R_{\text{vir}}) = 2.7 h_70^{-1} \text{Mpc} = 2.6 \pm 0.8 \times 10^{15} h_70^{-1} \text{M}_\odot \).

On the other hand, it is commonly accepted that A1914 hosts a merging event, and so velocity dispersion and X-ray temperature could be enhanced (e.g. Schindler & Müller 1993; Ricker & Sarazin 2001). Our analysis fails to separate the cluster substructures in the velocity space. We have to assume the result derived from the 1D-KMM method (Section 3.4, i.e. the two best Gaussians obtained there, despite their low significance). According to these results, the secondary group presents a very small velocity dispersion and its mass can be neglected with respect to the main system. For the main system \( \sigma_{v,\text{main}} \sim 980 \text{ km s}^{-1} \) which leads to \( M(< R_{\text{sys}}) = 2.2 h_70^{-1} \text{Mpc} = 1.4 \times 10^{15} h_70^{-1} \text{M}_\odot \). Hereafter, we consider as reliable the mass range \( M_{\text{sys}} = 1.4-2.6 \times 10^{15} h_70^{-1} \text{M}_\odot \) for the whole A1914 system.

The above value of \( \sigma_{v,\text{main}} \) is in agreement with \( \sigma_{v,\text{SIS}} = 846 \pm 87 \) estimated from the weak lensing analysis by Okabe & Umetsu (2008). For a punctual comparison with the projected mass computed by Okabe & Umetsu (2008) within \( R = 7 \text{ arcmin} \), we project and rescale our mass estimate \( M_{\text{sys}} \) assuming the cluster follows a Navarro–Frenk–White (NFW) profile, taking a mass concentration parameter \( c \) from Navarro, Frenk & White (1997)

\[ \beta_{\text{spec}} = \sigma_v^2 / (kT_X / \mu m_p) \text{ with } \mu = 0.58 \text{ the mean molecular weight and } m_p \text{ the proton mass.} \]

### Table 2. 2D substructure detected in the CFHT photometric data.

<table>
<thead>
<tr>
<th>2D subclump ((r = r_{\text{Mag}}))</th>
<th>(N_S)</th>
<th>(\alpha, \delta (J2000))</th>
<th>(\rho_S)</th>
<th>(\chi^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE ((r &lt; 21))</td>
<td>167</td>
<td>26:02:2.9, 49:46</td>
<td>1.00</td>
<td>104</td>
</tr>
<tr>
<td>SW ((r &lt; 21))</td>
<td>176</td>
<td>25:52:0.4, 18:12</td>
<td>0.54</td>
<td>53</td>
</tr>
<tr>
<td>No. 2 ((r &lt; 21))</td>
<td>204</td>
<td>25:02:2.5, 57:57</td>
<td>0.27</td>
<td>44</td>
</tr>
<tr>
<td>No. 1 ((r &lt; 21))</td>
<td>99</td>
<td>24:49:3.4, 37:56</td>
<td>0.20</td>
<td>26</td>
</tr>
<tr>
<td>NE ((21 \leq r &lt; 22))</td>
<td>90</td>
<td>26:06:7.4, 59:53</td>
<td>1.00</td>
<td>24</td>
</tr>
<tr>
<td>SW ((21 \leq r &lt; 22))</td>
<td>96</td>
<td>25:53:0.4, 58:52</td>
<td>0.86</td>
<td>18</td>
</tr>
<tr>
<td>No. 3 ((21 \leq r &lt; 22))</td>
<td>46</td>
<td>26:30:8.5, 54:25</td>
<td>0.62</td>
<td>15</td>
</tr>
<tr>
<td>No. 2 ((21 \leq r &lt; 22))</td>
<td>80</td>
<td>25:30:4, 59:13</td>
<td>0.62</td>
<td>13</td>
</tr>
</tbody>
</table>

Figures used in this section are as follows:

- Figure 9. Projected spatial distribution and isodensity contours (CFHT likely galaxy members with \( r_{\text{Mag}} < 21 \) (top panel), \( 21 \leq r_{\text{Mag}} < 22 \) (middle panel) and \( 22 \leq r_{\text{Mag}} < 22.5 \) (bottom panel). Contours were estimated using the 2D-DEDICA method. \( 'x' \) symbols note the NE and SW clumps in the upper and middle panel, while \( '1' \) and \( '2' \) symbols mark the position of BCG1 and BCG2. The numbers indicate the positions of the four galaxy clusters listed by NED within 20 arcmin from the cluster centre and having estimated or photometric redshift close to A1914 (\( \Delta z < 0.06 \)), in order of increasing \( \Delta z \). The circles indicate the cluster region within 2 \( h_70^{-1} \) Mpc at the cluster distance, i.e. somewhat smaller than the virial radius (2.2–2.7 \( h_70^{-1} \) Mpc, which is determined by the adopted model).
and correcting by the factor $1 + z$ (Bullock et al. 2001; Dolag et al. 2004, here $c \sim 4$). We obtain $M_{200}\,2d(< R = 1.2\ h_{70}^{-1}\ Mpc) = (1.1 - 2.0) \times 10^{15}\ h_{70}^{2}\ M_{\odot}$, in agreement with that $M_{200}\,2d(< R = 7\ arcmin) = (4.0 \pm 1.55) \times 10^{14}\ h_{70}^{2}\ M_{\odot}$ is a lower bound to the true enclosed mass (Okabe & Umetsu 2008). Instead, there is some tension between our value of $\sigma_{V\,\text{mean}}$ and the velocity dispersion estimate computed using redshifts from the on-going Hectospec Cluster Survey (Rines, Geller & Diaferia 2010), $\sigma_{V\,\text{Rines}} = 698^{+46}_{-38}\ \text{km}\ \text{s}^{-1}$. This explains the difference between our and their virial mass estimate $M_{200}\,\text{Rines} \sim 6.0 \times 10^{14}\ h_{70}^{-1}\ M_{\odot}$, as obtained rescaling the value of $M_{100}\,(R_{100} \sim 1.3\,\text{Mpc})$ and thus $M_{200} \sim 0.9M_{100}$ for a NFW profile (Eke et al. 1996).

### 4.2 Cluster structure

Our 2D analyses confirm the existence of an important bimodal structure elongated in the NE–SW direction and find two significant peaks: the NE one closer to BCG2 and the SW one closer to BCG1, although not perfectly centred on the two BCGs.

The analysis of Govoni et al. (2004) shows that the X-ray peak is displaced with respect to the BCGs positions. They find that X-ray maximum is at south with respect to BCG2 (see their Fig. 5a). Similarly, we also find that the X-ray peak does not coincide with our peaks in the galaxy density (see our Fig. 1). The offset between the optical and X-ray peaks suggests a post-merger cluster but, as noted by Govoni et al. (2004), the X-ray features are not typical (e.g. simulations by Roettiger, Stone & Mushotzky 1998). In fact, their analysis shows the presence of a NE–SW arc-like hot region crossing through the cluster centre, while the X-ray emission is elongated in the WNW–ESE direction, someway perpendicular to that described by the two galaxy/mass concentrations. Govoni et al. (2004) interpreted this observational scenario as due to a large impact parameter merger.

We add four contributions to the comprehension of the A1914 merging scenario. These contribute are (1) the relative importance of the NE and SW subclumps; (2) the merger is likely most contained in the plane of the sky, as suggested by the failure of 1D and 3D structure analysis methods in detecting the two galaxy subclumps (Pinkney et al. 1996); (3) A1914 is embedded in a rich large-scale structure that suggests that cluster accretion happens along two specific directions, NE–SW and NW–SE; (4) the presence of HVG, a minor external group of uncertain nature.

Point (1): the NE subcluster, close to BCG2 and the X-ray peak, has higher density than the SW subcluster, close to BCG1. However, the SW subcluster is the richer – and likely the more massive as shown by the respective galaxy population at end of Section 3.5 and Table 2, and by the respective velocity dispersions. This agrees with the result of the gravitational lensing analysis by Okabe & Umetsu (2008), where the peak C1, which is related to BCG2, is the highest density peak in the mass distribution, while the second density peak C2, related to BCG1, is suggested to be the primary cluster centre.

The point (2) suggests a similarity between A1914 and the well-known cluster Abell 754 (hereafter A754). A754 is a bimodal cluster where two obvious subsystems collide in the plane of the sky, showing an X-ray emission profile elongated and perpendicular to that of the two optical clumps (Zabludoff & Zaritsky 1995). The X-ray peak is closer to the denser optical peak, reminding us once more the similarity with A1914. As for A754, the gross X-ray morphology has been first explained with a non-zero impact parameter (Henry & Briel 1995), but more recent and detailed analyses suggest a more complex merger scenario, possibly involving a third substructure or a mass of cool gas disengaged from its previous host galaxy group and presently sloshing (Markevitch et al. 2003). In fact, a shock is found in front of the denser optical peak, as usual in head-on mergers (Macario et al. 2011).

Point (3): according to their estimated redshift, both galaxy systems No. 1 and No. 2 are likely to be connected to A1914. No. 1, i.e. the cluster NSCS J142452+373753 (Lopes et al. 2004), lies at SW. This and the merger axis of the two subclusters strongly support the idea that A1914 is accreting groups from a filament aligned with the NE–SW direction. No. 2, i.e. the cluster 400d J1425+3758 (Burenin et al. 2007), is a massive system (with $T_X > 5\ \text{keV}$ since included in the 400 Square Degree ROSAT PSPC Galaxy Cluster Survey) lying at NW, at the border of the virial radius of A1914, somewhat along the direction of the NW–SE elongated bright feature of the radio emission. Thus, No. 2 traces the NW–SE direction of a likely second filament accreting on to the cluster. This suggests a merging scenario more complex than the simple bimodal one for A1914.

Point (4): the group HVG, although very poor, is also clearly detected as a separate group in the projected phase space (see Fig. 4). Its nature is instead not clear. In this sense, we think that the main collision between the two substructures may have produced out-flying galaxies as predicted by simulations (e.g. Czoske et al. 2002; Sales et al. 2007) and detected in a few clusters (e.g. in Abell 3266 by Quintana, Ramírez & Way 1996; Flores, Quintana & Way 2000; in CL 0024+1654 by Czoske et al. 2002). This ipothesis is supported by the fact that the system has not a circular morphology but six out of eight galaxies trace a large strip. Moreover, four out of eight galaxies show emission lines, thus suggesting a possible star-forming activity triggered by the cluster merger. Alternatively, HVG could be a group in pre-collision phase with A1914, as well as a completely unbound group. Anyway, it is likely so poorly massive that can be considered a secondary detail in the cluster dynamics.

### 4.3 Bimodal model

In this section, we present our efforts to unravel the dynamics of the merger between the two main subclusters in the SW–NE direction with a simple bimodal model, assuming that this collision causes (at least part of) the diffuse radio emission. Following the method detailed for other DARC clusters (see e.g. Abell 520 in Girardi et al. 2008; Abell 2345 in Boschin, Barrena & Girardi 2010), we apply the two-body model (Beers, Geller & Huchra 1982; Thompson 1982) to evaluate the time-scales of the merger. This simple model assumes two point-mass bodies and a zero impact parameter. The model takes into account three parameters. These are the mass of the whole system, $M_{\text{sys}}\,(1.4 - 2.6 \times 10^{15}\ h_{70}^{2}\ M_{\odot}$, see above), the relative line of sight velocity in the rest frame, $\Delta V$, and the projected linear distance between the two substructures, $D$. As for the relative motion parameters, we consider our more reliable results, i.e. the estimate $\Delta V = 140\ \text{km}\ \text{s}^{-1}$ obtained from our 1D analysis, and the estimate $D \sim 0.4\ h_{70}^{-1}\ \text{Mpc}$ obtained from our 2D analysis. Because of the small radiative life of relativistic electrons and as a comparison with other radio haloes clusters (e.g. Barrena et al. 2002; Girardi et al. 2008), we assume an elapsed time, $t$, for the core crossing of few fractions of Gyr. We consider two different cases: $t = 0.1$ and 0.3 Gyr.

Fig. 10 compares the model solutions as a function of $\alpha$, where $\alpha$ is the projection angle between the plane of the sky and the line connecting the centres of the two clumps, with the mass estimate of the system $M_{\text{sys}}$. At $t = 0.1\ \text{Gyr}$, the solution is bound and outgoing (BO) with $\alpha \sim 10 - 25^\circ$, in agreement with the fact that we expect a merging axis mostly contained in the plane of the sky. At
t = 0.3 Gyr, the model predicts unlikely angles \( \alpha > 60^\circ \). Even when considering as \( M_{\text{sys}} \) the virial mass value by Rines et al. (2010, see our Section 4.1), the model with \( t \sim 0.1 \) Gyr should be preferred.

5 CONCLUSIONS

In conclusion, A1914 shows clear evidence of a recent cluster merger along the NE–SW direction and almost contained in the plane of the sky. The presence of an ongoing merger and the large mass are the main features of typical clusters with radio haloes described in the literature. The large-scale structure in the environment of A1914 suggests evidence of a second direction of cluster accretion, NW–SE. This merging axis is likely related to the bright feature of the diffuse radio emission. Thus, we argue that the unusual radio appearance of A1914 is due to the complexity of the merger. Indeed, we point out that A1914 appearance resembles that of A774 where a complex merger scenario or a sloshing core seems to be the possible explanations. Only deeper X-ray data and many redshift measurements in a more extended cluster region could allow us to better understand the dynamics of A1914.

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