

The Dynamics of the Wide-angle Tailed (WAT) Galaxy Cluster A562

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Abstract

We present the first in-depth dynamical analysis of the archetypal wide-angle tailed (WAT) cluster A562. We have combined Gemini observations with archival data from the literature to form a sample of 76 cluster members and derived a mean redshift of 0.1088 ± 0.0004 and a velocity dispersion of $919 \pm 116 \text{ km s}^{-1}$. This relatively large velocity dispersion suggests either a very massive cluster ($M_{dyn} > 6.9 \times 10^{14} M_{\odot}$) and/or a merger system. The merger model is supported by a non-Gaussian galaxy velocity distribution, an elongated spatial distribution of likely cluster members, and an elongated X-ray emitting gas. This scenario would generate the bulk flow motion of the intracluster medium that can exert enough ram pressure to bend the radio jets. Thus, our observations support the model in which a recent off-axis merger event produced the cluster wide conditions needed to shape the WAT in A562.

Unified Astronomy Thesaurus concepts: Galaxy clusters (584); Extragalactic radio sources (508); Radio galaxies (1343); Tailed radio galaxies (1682)

1. Introduction

Clusters of galaxies grow and evolve by continuous accretion of mass through merger events. These mergers produce physical effects on the intracluster medium (ICM) such as bulk flows of gas, shocks, and the formation of substructure in the gas density and temperature. This stormy weather (Burns 1988) can be responsible for the morphology and perhaps the formation of the so-called wide-angle tailed (WAT) radio sources.

WAT radio sources were first classified as such by Owen & Rudnick (1976) based on their particular bent morphology. They have radio powers are at the limit between the very powerful FR IIs and the weaker FR Is. The size of the radio lobes extends beyond the limits of the galaxy host, and thus, makes them useful probes of the intracluster medium (ICM). In addition, the hosts for the WATs are central dominant galaxies (D or cD galaxies; Rudnick & Owen 1976) which are expected to either be at rest or have small peculiar motions in the cluster. Otherwise these galaxies could be destroyed by tidal forces.

Several models have been proposed for explaining their peculiar radio morphology. Early models proposed that radio bent sources are produced by individual plasma blobs that are ejected by the active galactic nucleus (AGN) and adopt the observed geometry due to buoyancy or interactions with the ICM (Jaffe & Perola 1973; Fomalont & Bridle 1978). However, Burns et al. (1979) found that the physical properties of these blobs were not consistent with the observations of the WAT 1159+583. A slight variation of this model was proposed by Leahy (1984) who postulated that the AGN jets left trails that in their wake adopted the observed bent morphology. Other models assumed that the observed morphology is produced not by blobs but by actual AGN jets that are bent by buoyancy and pressure imbalances (Schindler & Prieto 1997), instabilities at the interstellar medium (ISM)/ ICM boundary (Patnaik et al. 1986), electrodynamic effects (Eilek et al. 1984), or ram pressure (Begelman et al. 1979; Feretti et al. 1985; O'Donoghue et al. 1993). Sakelliou et al. (1996)

proposed a combination of ram pressure and buoyancy to explain the complex morphology of the WAT in 4C 34.16.

In order for the ram pressure model to work, there must be sufficient relative velocity between the AGN and the ICM. The estimated relative velocity that is needed to produce the bending of the jets depends on fundamental jet properties such as velocity and density. For instance, Gómez et al. (1997) estimated that relative velocity between 400 and 2500 km s⁻¹ would be needed for slow jets ($v_j \sim 0.0075c$). Jetha et al. (2006) expanded this analysis to faster jets ($v_j \sim 0.6c$) and concluded that lighter jets might need even lower galaxy velocities.

The hosts for the WATs are central dominant galaxies which are expected to be at rest or have very small peculiar motions in the cluster. So if the host galaxy does not have a significant peculiar velocity, what could be the source of the large relative velocity between the jets and the ICM needed to bend the WATs? The most accepted scenario is that the ram pressure is produced by cluster mergers. There is evidence suggesting that most WAT sources are located in clusters that show the effects of recent mergers such as substructure in the X-ray emitting gas (Gómez et al. 1997), the galaxy distribution, or the presence of non-Gaussian velocity distributions (Pinkney et al. 2000). Moreover, numerical simulation of cluster mergers predict that large bulk flow motions develop during a merger. They are produced just after the core crossing and can last for as long as 1 Gyr (Loken et al. 1995; Roettiger et al. 1996). These flows develop along the merger direction and are parallel to the elongations of the X-ray emitting gas that are produced during the merger. Even though this model seems to explain most WATs, there are a few counterexamples (e.g., the WAT in 3C 130 as described by Hardcastle 1998) that merit further work.

A562 (Abell et al. 1989) is a nearby cluster that hosts a prototypical WAT radio source (Gómez et al. 1997; Douglass et al. 2011). This radio source is also known as 3C 169 (van den Bergh 1961) or 0647+693 (O'Dea & Owen 1985) and exhibits the typical bent shape of its twin jets. Jetha et al. (2006) calculated that a galaxy velocity of 870 km s⁻¹ would be needed to bend this source based on the radio properties of



Figure 1. Color-magnitude diagram derived from GMOS-N data for galaxies in the A562 field. The crosses show all the likely galaxies in this field (CLASS-STAR < 0.9). The circles show the cluster galaxy subsample that we derived (i.e., they had colors in the 0.3 < g' - r' < 1.7 range and were brighter than $m_{r'}$ of 18.6) and that we could fit on the four masks. Of these, the solid circles show the spectroscopically confirmed cluster members.

the jet and the X-ray properties of the surrounding gas. They argued that such a velocity is probably too large for a centrally located galaxy and can only be produced by a cluster merger. In fact, Miller et al. (2002) reported a recessional velocity for this galaxy of $32,448 \text{ km s}^{-1}$ and a cluster recessional velocity of 32,758 km s⁻¹ based on the observations of six other cluster members. These measurements reveal a small peculiar velocity of 310 km s^{-1} for this WAT and support the merger hypothesis. Douglass et al. (2011) have analyzed Very Large Array (VLA) and Chandra observations that further support the merger model. Their Chandra analysis confirmed an elongated X-ray emission along the line that bisects the jet bending which was first detected in ROSTAT data by Gómez et al. (1997). Moreover they reported that the X-ray temperature spatial distribution shows signatures of a recent cluster merger. Thus, they found regions of hot gas probably caused by shock heating. Finally, they found that the excess X-ray emitting gas located between the WAT lobes has a high abundance and proposed that it might be a remanent cool core disrupted by a merger.

In this paper, we combine recent recessional measurements of 75 cluster members with archival data of one cluster member in order to confirm the small peculiar motion of the WAT. Furthermore, we use these data for conducting statistical analysis in order to test the merger hypothesis and model the type of merger experienced by this cluster. In this way, we can further constrain the relative velocity and the jet properties for this prototypical WAT radio source. We report our optical observations in Section 2 and their data analysis in Section 3. Our interpretations are discussed in Section 4. Finally, we summarize our findings in Section 5. Note that we use $H_0 =$ 70 km s⁻¹ Mpc⁻¹, $\Omega_{\Lambda} = 0.714$, and a flat universe throughout the paper, so that 1' \simeq 119.8 kpc. All errors are quoted to the 1 σ level.

2. Observations

In this section, we report the optical and X-ray observations of A562. We start by describing the pre-imaging data used to



Figure 2. Distribution of galaxies in the A562 field derived from GMOS-N data. The crosses show all the likely galaxies in this field (CLASS-STAR < 0.9). The circles show the cluster galaxy subsample that we derived (i.e., they had colors in the 0.3 < g' - r' < 1.7 range and were brighter than $m_{r'}$ of 18.6) and that we could fit on the four masks. Of these, the solid circles show the spectroscopically confirmed cluster members. The blue octagons show the approximate edge of the field of view of each mask.

design the multi-object spectroscopic (MOS) masks. Next, we describe the Gemini North Multi-Object Spectrograph (GMOS-N) MOS spectroscopic observations and their reduction. Finally, we describe our analysis of archival Chandra X-ray observations that will be used to compare the distribution of the galaxies with the distribution of the X-ray emitting gas.

2.1. Optical Imaging

Imaging data in the g' (120 s total) and r' bands (120 s total) were obtained with the GMOS instrument mounted at the Gemini North telescope. We used four different pointings aimed at A562 in order to map out the galaxies located within \sim 5' of the cluster center. The observations were carried out in queue mode (program GN-2008B-Q-97 and GN-2009B-Q-46) with an overall seeing of $\sim 1.0^{\circ}$ and thin cirrus on the sky. The images were bias subtracted and flat fielded with sky twilight flats. Next, the GMOS images were mosaiced and coadded into final g' and r' band images. We identified and measured the properties of the galaxies using the SExtractor program (Bertin & Arnouts 1996). We adopted the MAG-BEST output from SExtractor to estimate the galaxy magnitude. Even though the observations were not obtained under photometric conditions, we converted the observed counts into approximate magnitudes using the zero-point filter values listed on the Gemini public webpages. We are aware that the absolute magnitudes could be off by up to ~ 0.3 mag. We combined the SExtractor output from the g' and r' images to construct a color-magnitude diagram. The color term should not be severely affected by the uncertainty in the absolute magnitude of the galaxies. Figure 1 shows the color-magnitude diagram and Figure 2 shows the distribution on the sky of 821 objects derived from the SExtractor output. All of these objects are likely to be galaxies as they had the CLASS-STAR < 0.9. We selected a subsample

 Table 1

 GMOS-South Spectroscopic Setup

Mask	Grating Rul- ing Density	Central Wavelength	Full Range	Blaze Wavelength
	(lines mm^{-1})	(Å)	(Å)	(Å)
mask1	600	5300, 5500	2760	4610
mask2	600	5300, 5500	2760	4610
mask3	600	4600, 4800	2760	4610
mask4	400	7800, 8000	4160	7640

of 481 of these 821 as candidate cluster members based on their position on the color-magnitude diagram (i.e., 0.3 < g' - r' < 1.7 and $m_{r'} < 18.6$). This color cut is wide enough to include all the red sequence galaxies and other likely cluster members.

Note that we also observed the core of the cluster with the DEep Imaging Multi-Object Spectrograph (DEIMOS) instrument at W. M. Keck Observatory in the V (900 s total time), R (900 s total time), and I bands (540 s total time). These observations were obtained in 2017 March 30 under clear conditions and 0."8 seeing. These images will be used to look for multiple nuclei in the WAT host.

2.2. Optical Spectroscopy

We observed 131 unique targets in A562 with the GMOS-N in MOS mode as part of the queue program GN-2010B-Q-90 in 2010 November. Each mask had a field of view of $\sim 5' \times 5'$ that allowed us to fit at least 30 candidate galaxies. In order to observe at least 100 galaxies, we designed four GMOS masks covering a region of $\sim 10' \times 10'$. The sky coverage of the four masks can be seen in Figure 2. In our spectroscopic setup, we used the B600+G5307 grating that has an average spectral resolution of $\sim 180 \text{ km s}^{-1}$ ($R \sim 1700$) or ~ 0.5 Å per pixel centered between 520 and 530 nm (see Table 1). These wavelengths correspond to the spectral location of the redshifted Ca[II] absorption lines of early-type galaxies which constitute the bulk of our cluster candidates. The observations consisted on two 1800 s exposures spectrally shifted to minimize the effects of cosmic rays, bad pixels, and chip gaps.

To reduce the spectroscopic data we used the Gemini IRAF package and followed the standard reduction recipe. First, we bias corrected and flat fielded the data, removed cosmic rays and mosaiced the science and arc frames. We wavelength calibrated the arc frames row by row and visually inspected the corrected arc images before applying the calibration to the science data. Then, we defined the apertures for each galaxy and extracted and sky-subtracted 1D spectra from the 2D spectra. Finally, the two 1800 s spectra were coadded by shifting them to a common wavelength frame. Typical error of the wavelength calibration was about 0.5 Å.

To measure the radial velocities of the observed galaxies, we used the tasks *fxcor* from *RV* and *emsao* from *RVSAO*. *Fxcor* cross-correlates the observed spectra with high signal-to-noise spectra templates for different galaxy types obtained from the Sloan Digital Sky Survey (SDSS) database. On the other hand, *emsao* finds emission lines, computes redshifts for each identified line, and combines them into a single radial velocity. The typical error for radial velocities (including the error due to wavelength calibration and the trace) was $\lesssim 100 \text{ km s}^{-1}$. Note that we observed 11 objects twice. The mean difference

between the measurements of these 11 repetitions is 75 km s^{-1} and confirms the velocity error quoted above.

2.3. Chandra X-Ray Observations

A562 was observed by the Chandra Advanced CCD Imaging Spectrometer S-array (ACIS-S) instrument in 2006. We retrieved the data (obs. ID 6936) from the Chandra Data Archive and analyzed them with Chandra Interactive Analysis of Observations (CIAO) version 4.10. We filtered the data by analyzing the light curves on the S3 chip. Thus, we ended with an actual exposure time of 51,392 s. Next, we masked out point sources and created exposure maps in order to map the extended cluster X-ray emission in the 0.2–10 keV spectral region. As expected, the final map (see Figure 3) shows the same properties initially reported by Douglass et al. (2011).

3. Analysis of the Optical Data

3.1. Completeness of the Spectroscopic Sample

After reducing and processing the spectroscopic data, we were able to measure the velocities for 102 objects (Table 2). Although our sampling is not complete, we believe that it is representative of the galaxy population in A562. For example, of the galaxies targeted for spectroscopy, we have been able to observe over 50% of those brighter than r' = 17. (and roughly 30% at r' = 18). We have also compared the radial distribution of the observed galaxies with the distribution of all the 481 galaxies selected as candidate cluster members (see Section 2.2). We computed the ratio of the number of observed galaxies to the number of candidate members in three radial bins, each $2'_{0}$ (~225 kpc) wide, and centered on the brightest galaxy in the cluster. We obtained values of 0.45, 0.27, and 0.29 for the ratios in the three bins. This distribution shows that we selected relatively more galaxies toward the center of the cluster. This is expected because the four masks slightly overlap toward the center of the cluster (see Figures 2 and 3).

3.2. Mean Redshift and Velocity Dispersion

The 102 galaxies with redshifts in Table 2 include cluster members, foreground, and background galaxies. In order to increase the number of galaxy velocities available for our dynamical study we combine this sample with data for 11 galaxies obtained from the literature (Miller et al. 2002). We find that our measurements and the data from Miller et al. (2002) have two galaxies in common. The mean difference between these measurements is 130 km s^{-1} which is comparable with the average error in the measurements and do not reveal a systematic difference. Since we plan to test for substructure by combining the spatial and velocity data, we decided to apply a velocity and a spatial filter. First, we only consider galaxies located within a radius of 7'. Next, we used an iterative 3σ clipping criterion (Yahil & Vidal 1977) to identify the cluster members. Most of the outliers were rejected after the first iteration. Thus, we were left with 76 likely cluster members. The velocities for 75 of these galaxies were derived from our own observations (labeled as such in Table 2); the velocity for one galaxy was obtained from the literature (with velocity of 33,043 km s⁻¹ for a galaxy located at R.A. = 06 50 38.27 and decl. = 69 24 19.9 from Miller et al. 2002).



Figure 3. Left: contours of an adaptively smoothed Chandra image of the cluster in the 0.2-10 keV energy range. The black crosses show the positions of the 76 spectroscopically confirmed cluster members. Note that the X-ray emission is elongated in the northwest–southeast direction. The red cross marks the position of the WAT galaxy. Right: DEIMOS false color image (*V*, *R*, and *I* bands) of the central region of A562 with overlaid X-ray (red) and 1.4 GHz VLA (in blue from E. M. Douglass 2020, private communication) contours.

The density of the cluster candidates and spectroscopically confirmed members versus the position in the X-ray image is shown in Figures 6 and 5 respectively. As we are dealing with small number statistics, we used robust bi-weight estimators for the mean and velocity dispersion in order to characterize the distribution of redshifts (Danese et al. 1980). We used the astropy (Astropy Collaboration et al. 2013, 2018) implementation of the ROSTAT program (Beers et al. 1990) bi-weight estimators. We measured a bi-weight estimator for the location of the cluster of $32,643 \pm 120 \,\mathrm{km \, s^{-1}}$ (1 σ errors) with a velocity dispersion (cosmologically corrected) of $\sigma_{\rm vel} = 919 \pm$ 116 km s⁻¹ (1 σ errors determined with a bootstrap method). We note that the measured cluster redshift of 0.1088 is in agreement (within the errors) with the 0.1092 value quoted by Miller et al. (2002). Its location on the sky and its redshift are shown in Figures 2 and 4 respectively.

We note that due to the fact that the GMOS field only samples the inner 7' (or 839 kpc) of the cluster the velocity dispersion could be biased and overestimate the actual value by as much as 10% (see Saro et al. 2013). Therefore, in what follows, we will use a conservative correction factor of ~10% to the velocity dispersion so that the effective velocity dispersion $\sigma_{vel,eff} = 827 \text{ km s}^{-1}$.

3.3. WAT Peculiar Motion

We measure a negligible peculiar motion of the WAT with respect to the cluster location. The recessional velocity of the WAT is $32,750 \pm 60 \text{ km s}^{-1}$ and the cluster location has a value of $32,643 \pm 120 \text{ km s}^{-1}$. Thus, the peculiar velocity is $107 \pm 134 \text{ km s}^{-1}$ (corrected to the cluster rest frame). Thus, the WAT galaxy is at rest with respect to the cluster. This is represented on Figure 4 which shows the velocity of the WAT and the cluster location with their 99.7% error bar.

3.4. Cluster Mass

We have computed the mass of the cluster using the $M_{\rm dyn}$ relation from Saro et al. (2013)

$$M_{\rm dyn} = \left[\frac{\sigma_{\nu}}{A \times h_{70}(z)^C}\right]^B \times 10^{15} \, M_{\odot},\tag{1}$$

where $M_{\rm dyn}$ is the dynamical mass within a virial radius and the constants used are A = 939, the exponent B = 2.91, and the exponent C = 0.33, according to Saro et al. (2013). In our case, we use the effective velocity dispersion of $\sigma_{\rm vel,eff} = 898 \pm 220 \,\rm km \, s^{-1}$ and calculate a value of $M_{\rm dyn} = 6.9 \pm 2.8 \times 10^{14} M_{\odot}$.

3.5. Dynamical State

3.5.1. Substructure

In order to determine the dynamical state of the cluster, we examined the velocity and spatial distribution of the galaxies using 1D, 2D, and 3D statistical tests. The 1D statistical tests look for non-Gaussianity and/or substructure in the velocity distribution. The 2D tests look for asymmetries and substructure in the spatial distribution of the galaxies. Finally the 3D tests, which combine the velocity and position information, look for other merger signatures.

We run a modified version (Pinkney et al. 1996) of the ROSTAT (Beers et al. 1990) battery of tests on the velocity distribution (Figure 4) to quantify any non-Gaussianity. Kurtosis is detected by the $W^2 - stat$ with a probability of Gaussianity of 4%, $A^2 - stat$ with a probability of 5%, and $U^2 - stat$ with a probability of 3%. The velocity distribution appears asymmetric. Thus, we measure an asymmetry index (AI; Bird & Beers 1993) -0.7 that has a probability of 8% of being Gaussian and a tail index (TI; Bird & Beers 1993) value of 1.4 that has only a probability of 1% of being Gaussian.

 Table 2

 Spectrocopic Targets

id	R.A. (2000)	Decl. (2000)	Velocity (km s ⁻¹)	Error (km s^{-1})	Notes
1	6 52 29.03	69 23 8.62	32510	50	Member
2	6 52 33.43	69 16 3.14	36680	40	
3	6 52 33.44	69 15 26.07	30970	40	Member
4	6 52 35.33	69 23 40.20	168400	190	
5	6 52 36.55	69 22 3.14	29630	90	Member
6	6 52 37.63	69 19 3.54	31980	70	Member
7	6 52 37.82	69 21 54.51	32970	210	Member
8	6 52 39.01	69 17 5.22	32750	40	Member
9	6 52 40.66	69 18 50.44	32330	30	Member
10	6 52 44.31	69 18 22.97	100500	100	
11	6 52 45.03	69 19 21.42	31130	80	Member
12	6 52 46.01	69 22 0.91	34760	140	Member
13	6 52 48.14	69 19 37.27	32840	50	Member
14	6 52 48.72	69 19 15.71	32890	60	Member
15	6 52 49.30	69 22 41.37	99580	40	
16	6 52 51.56	69 21 2.88	32010	80	Member
17	6 52 53.15	69 24 15.00	62220	30	
18	6 52 57.00	69 24 9.04	73360	40	
19	6 52 58.64	69 24 24.01	31330	50	Member
20	6 52 59.16	69 16 45.22	32630	90	Member
21	6 52 59.82	69 19 29.41	31150	130	Member
22	6 52 59.98	69 16 57.06	32380	50	Member
23	6 53 1.18	69 20 42.80	77020	90	
24	6 53 1.45	69 17 16.97	32070	40	Member
25	6 53 2.27	69 20 24.73	32740	30	Member
26	6 53 2.94	69 17 12.44	31040	80	Member
27	6 53 5.67	69 23 5.02	111500	30	
28	6 53 6.17	69 16 25.75	26360	30	
29	6 53 7.69	69 15 46.61	33350	60	Member
30	6 53 7.82	69 19 41.20	32190	50	Member
31	6 53 8.93	69 20 42.03	32180	40	Member
32	6 53 10.03	69 20 3.09	32830	80	Member
33	6 53 10.07	69 19 33.67	31870	/0	Member
34 25	6 53 10.55	69 19 7.63	31980	100	Member
35 26	6 53 13.39	69 20 28.74	33510	70	Member
20 27	6 52 14 07	60 10 40 70	34270	30	Member
31 20	6 53 14.07	69 19 49.79	33400	40	Member
20 20	6 52 15 05	60 20 14 21	32800	10	Member
39 40	6 53 15 25	60 22 5 20	20200	40	Mombor
40	6 53 16 05	60 17 55 67	32970	90	Member
41	6 53 16.05	69 17 18 02	32910	70	Member
42 13	6 53 16 38	69 20 5 31	32480	60	Member
ч.5 ЛЛ	6 53 16 71	69 23 22 27	33840	40	Member
45	6 53 16 77	69 17 46 72	32740	90	Member
46	6 53 18 32	69 18 9 90	29350	60	Wielinder
40	6 53 19 51	69 15 30 95	26360	60	
48	6 53 20.06	69 19 31 69	31320	60	Member
49	6 53 20.00	69 16 11 63	33350	70	Member
50	6 53 21 45	69 19 51 77	32750	60	WAT
51	6 53 21 88	69 15 58 15	33820	60	Member
52	6 53 22 29	69 21 33 12	30890	50	Member
53	6 53 22 91	69 23 48 06	33190	30	Member
54	6 53 23 11	69 23 43 25	28150	40	
55	6 53 23.82	69 15 57.32	32420	90	Member
56	6 53 24.57	69 23 39.74	61950	70	
57	6 53 24.91	69 23 37.57	17020	40	
58	6 53 25.35	69 19 54.27	32970	100	Member
59	6 53 26.12	69 18 8.72	32420	40	Member
60	6 53 26.85	69 16 33.14	51640	70	
61	6 53 27.19	69 19 53.20	32230	70	Member
62	6 53 27.56	69 18 41.62	32570	80	Member
63	6 53 28.66	69 20 9.79	32960	90	Member
64	6 53 31.52	69 23 29.88	32730	50	Member

(Continued)					
id	R.A. (2000)	Decl. (2000)	Velocity (km s ⁻¹)	Error (km s ⁻¹)	Notes
65	6 53 31.85	69 20 53.49	169300	60	
66	6 53 31.90	69 17 32.35	34560	60	Member
67	6 53 34.69	69 19 18.70	33330	70	Member
68	6 53 35.66	69 19 55.75	32840	70	Member
69	6 53 37.11	69 16 32.42	30900	70	Member
70	6 53 37.16	69 19 13.92	32510	90	Member
71	6 53 37.46	69 19 22.30	32750	80	Member
72	6 53 41.46	69 17 8.57	92040	80	
73	6 53 41.59	69 21 25.35	32710	40	Member
74	6 53 42.33	69 17 1.18	175300	70	
75	6 53 43.96	69 18 13.96	31950	70	Member
76	6 53 45.01	69 15 37.85	89980	110	
77	6 53 47.11	69 22 11.13	32300	90	Member
78	6 53 47.18	69 21 16.64	34520	60	Member
79	6 53 47.90	69 15 13.57	30450	80	Member
80	6 53 48.49	69 24 23.35	89680	40	
81	6 53 49.66	69 20 26.84	32030	150	Member
82	6 53 50.45	69 19 5.63	33000	60	Member
83	6 53 50.86	69 18 1.30	33170	230	Member
84	6 53 54.05	69 21 56.90	34390	220	Member
85	6 53 55.40	69 16 5.42	32040	70	Member
86	6 53 55.51	69 21 7.19	33350	50	Member
87	6 53 56.38	69 23 3.12	38760	50	
88	6 54 0.48	69 20 33.00	33000	40	Member
89	6 54 0.51	69 15 53.67	44450	60	
90	6 54 1.60	69 22 32.53	31690	130	Member
91	6 54 2.83	69 16 43.49	33170	70	Member
92	6 54 4.90	69 18 35.83	62870	80	
93	6 54 6.92	69 18 26.38	33440	60	Member
94	6 54 7.44	69 22 24.48	31770	40	Member
95	6 54 8.26	69 17 13.35	124700	70	
96	6 54 8.62	69 15 27.71	139400	80	
97	6 54 8.63	69 21 47.35	32500	50	Member
98	6 54 10.63	69 16 21.57	28600	200	
99	6 54 10.63	69 19 39.93	32960	70	Member
100	6 54 10.77	69 16 54.09	124600	130	
101	6 54 14.99	69 16 39.15	30910	70	Member
102	6 54 15.58	69 19 46.85	34510	190	Member





Figure 4. Velocity histogram of the galaxies in A562 The bin size is 250 km s^{-1} . The blue star shows the location of the WAT host and the red diamond shows the location of the robust bi-weight mean velocity. All the error bars show the 1σ error. We also overlay (green) a Gaussian distribution derived from the measured bi-weight mean velocity and dispersion.

Therefore, we found evidence for non-normality in the velocity distribution of the galaxies.

Next we examined the galaxy distribution for evidence of substructure. Figure 5 shows the spatial distribution of the spectroscopically confirmed galaxies. Their distribution shows a central peak and two elongations. The central peak coincides

with the peak of the X-ray emission. One elongation is toward the northeast and the other is toward the south southwest. In order to further explore this peculiar distribution, we have analyzed the spatial distribution of the most likely cluster members as selected from the color-magnitude diagram. Thus, we have selected 316 galaxies located within ± 0.3 mag of the red sequence (i.e., color-selected sample). Their distribution is shown in Figure 6. It is very similar to the distribution of the spectroscopically confirmed members in Figure 5. It shows a central clump elongated toward the northeast (parallel to the elongation found in Figure 5). This clump is slightly offset from the X-ray peak. It also shows an elongation toward the south which is similar to the one seen in Figure 5.

We assess the significance of the substructure by running a series of four tests on the color-selected sample: the angular separation (West et al. 1988) test (i.e., AST), the so-called β test (West et al. 1988), the Fourier elongation test (Pinkney et al. 1996), and the Lee Statistic (Lee 1979; Fitchett & Webster 1987). Of these, only the Lee statistics shows a marginal probability of substructure as seen in Table 3. This test looks for a significant split into two subsamples and confirms the bimodality hinted by Figure 6. We did not run the



Figure 5. An overlay of the spatial density of the 76 spectroscopically confirmed galaxy members (white contours) over a color scale image of the adaptively smoothed 0.2-10 keV X-ray emission. The contour values are 0.85, 1.1, 1.3, 1.5, 1.7, 1.9, 2.1, 2.4, and 2.6 galaxies $\operatorname{arcmin}^{-2}$. Note that the X-ray peak is slightly offset from the peak in the galaxy density and that the X-ray emission is elongated.



Figure 6. An overlay of the spatial density of the 316 galaxies selected based on their color as likely cluster members (white contours) over a color scale image of the adaptively smoothed 0.2-10 keV X-ray emission. The contour values are 2.3, 2.6, 2.9, 3.2, 3.5 3.8, and 4.2 galaxies $\operatorname{arcmin}^{-2}$. Note that the X-ray peak is aligned with the peak in the galaxy density and that the X-ray emission is elongated.

tests on the sample of confirmed members for two reasons. First, the color-selected sample has at least three times more galaxies. Second, the spectroscopic sample contains galaxies

 Table 3

 Substructure Tests for the Color-selected Sample

Substructure Test	Statistical Significance	Sensitivity
AST	0.63	clumping
Symmetry test (β)	0.95	asymmetry
Fourier elongation	0.93	elongation
Lee 2D	0.07	bimodality

Note. Column 3 is adapted from Pinkney et al. (1996).

preferentially located toward the cluster center due to the central overlap of the four masks as shown in Figure 2 in Section 3.1.

Finally, we looked for substructure using 3D tests that combine the spatial and kinematical positions of the galaxies. Please note that our spatial sampling of the galaxies is not uniform and this could affect the sensitivity of these tests. We ran four different tests on the data: the Lee 3D test (Pinkney et al. 1996), the Dressler-Schectman test (Dressler & Shectman 1988), the ϵ test (Bird 1993), and the α test (West & Bothun 1990). These tests did not find any significant evidence of substructure as reported in Table 4.

3.5.2. Clustering

It is possible that the substructure tests run before (Section 3.5.1) are insensitive to some types of mergers and clustering in the data. For instance, Pinkney et al. (1996) reported that these tests were very effective at detecting substructure and that was the reason we initially used them to analyze our data. However, we note that Pinkney et al. (1996) evaluated these tests using only a specific type of merger: simulated *head-on* mergers. Could these substructure tests be less effective in the case of non-head-on mergers? In order to be more thorough, we turned to use an exploratory data analysis as an alternative method to look for any previously undetected clustering in the data. Specifically, we used the astropy implementation of the Gaussian mixture models (GMM) as an additional method for objectively identifying galaxy densities especially for the 3D case that combines spatial and velocity information. This method was first used by Ashman et al. (1994) to detect bimodality on astronomical data sets. Since then the method has been used to look for substructure in individual clusters (e.g., Barmby & Huchra 1998; Biviano et al. 2017; Boschin et al. 2020).

If this cluster is undergoing a merger, hierarchical evolution suggests a bimodal cluster merger. Therefore, we concentrate on the GMM model that splits the data into two groups: group A with 56 members and group B with 20 members. Table 5 shows the properties of these two groups. Figure 7 shows overlays of the group A and B galaxy densities over the smoothed X-ray data. Interestingly, group A is compact and elongated and it is aligned with the main X-ray elongation. Group B on the other hand shows a peak to the south of the main group and is less concentrated than group A. Figure 8 shows a 3D scatter plot of the galaxies in spatial and velocity space. We also project the histograms of these groups. The galaxies in group A are more concentrated spatially and in velocity space than galaxies in group B. Moreover, group A is located at a slightly higher redshift than group B. Finally, the GMM allocates the WAT to galaxy group A with a probability greater than 0.99. In this case, the relative peculiar velocity of

 Table 4

 Substructure Tests for the 3D Sample

Substructure Test	Statistical Significance	Sensitivity
Lee 3D	0.82	Bimodality
α	0.79	Centroid shift with velocity
ϵ	0.11	Change in velocity dispersion and density with position
Δ	0.13	Change of velocity dispersion and mean velocity with position

Note. Column 3 is adapted from Pinkney et al. (1996).

Table 5 GMM Groups

Group Label	Number of Galaxies	Center R.A. (J2000)	Center Decl. (J2000)	Location (km s ⁻¹)	Scale (km s ⁻¹)
A B	56 20	6 53 20.6 6 53 24.5	69 19 26.4 69 19 16.3	32,661 32,118	947 1102

the WAT with respect to group A would also be negligible (89 \pm 135 $km\,s^{-1}$).

It is possible that these two groups trace the pre-merger components. Based on the velocity dispersion of them we can derive a mass ratio of 4:1 (based on their velocity dispersions). Another way is that the groups do not trace the pre-merger component. Thus, group A points to the highest galaxy density clump probably composed on the merging cores of the two merging clusters. Whereas group B is made up of the galaxies that have not mixed yet and are still trailing the cores of the premerger systems.

It is also possible that the GMM method can split the cluster into more than two components. Therefore, we used both the Akaike and Bayesian information criteria (AIC and BIC) to determine if splitting the data into more than two components is statistically significant. These criteria are based on combining the maximum likelihood computed for each model and correcting it by a function of the number of components. This is to prevent the condition at which the maximum likelihood is obtained when the number of components is equal to the number of elements. The best model would minimize these criteria. Figure 9 shows the BIC/AIC criteria as a function of the number of components for our 3D data. Even though these two criteria do not single out a bimodal model as the most statistically significant, they do prefer models with few components.

3.5.3. Dynamical State

In summary, the strongest optical evidence for a merging event comes from the skewness of the velocity distribution and from the galaxy density distribution. Figures 5 and 6 show an elongation and bimodality consistent with that seen in the X-ray image. This substructure is confirmed by the Lee statistical test when applied to the color-selected sample. It is worth mentioning that there is no single test that can determine the dynamical state of every cluster (Pinkney et al. 1996). Therefore, it is not surprising that some tests yield inconclusive results. After all, the sensitivity of a given test to detect substructure (or other perturbations such as asymmetry) depends on both the quality and completeness of the data available and on the properties of the merging system, such as mass ratio, merger epoch, and viewing angle (e.g., Pinkney et al. 1996; White et al. 2010). Interestingly, the GMM method finds clustering in the data and the GMM model with two components finds alignments between galaxy and gas clumps. Therefore, a more insightful approach would be to compare the observables with numerical simulations. This approach has already been applied with success to other clusters (e.g., Springel & Farrar 2007). We describe an initial qualitative attempt at this type analysis in the next section.

4. Discussion

A562 shows signatures of a cluster merger observed after core crossing. The spatial distribution and the thermal properties of the X-ray emitting gas are consistent with a post merger cluster. In their Chandra analysis, Douglass et al. (2011) reported an elongation of the X-ray emitting gas aligned with the line that bisects the jets of the WAT. Moreover, the distribution of gas in the core of the cluster deviates from an elliptical 2D β -model due to the presence of a clump of high metal abundance gas located in between the radio lobes. Interestingly, they proposed that the high metal abundance clump of gas might be the remanent of one of the pre-merger cluster cores. The substructure and elongation of the X-ray emitting gas and the alignment between the X-ray and the WAT jets are the typical signatures of a recent cluster merger. Note that a relative gas velocity of 1000 km s^{-1} is what is needed to bend the jets (Douglass et al. 2011). This type of bulk flow gas motion is produced during a merger and can only lasts for a couple of gigayears after core crossing (Roettiger et al. 1996). Moreover, we have measured a small relative velocity between the WAT host and the rest of the galaxies. Therefore, its contribution to the overall relative velocity between the WAT host and the ICM is negligible.

Our substructure analysis of the galaxy data is also consistent with a merger model. During a merger and depending of the merger parameters (i.e., epoch, viewing angle, and mass ratios) the velocity of the galaxies could show skewness and the spatial distribution could be elongated (Pinkney et al. 1996). In the case of A562, we have shown that the elongation of the spatial distribution of the galaxies is aligned with the elongation of the X-ray emitting gas. Depending on the merger parameters it might be possible to identify some of the premerger parameters. For instance, during core crossing the spatial distribution of the galaxies would be mixed whereas the galaxies would be segregated in velocity space. This is due to an ever decreasing center of mass separation and an increasing relative velocity before core crossing (maximum infall velocity) and even after core crossing (as the pre-merger cluster galaxies oscillate toward a relaxed state). This will hold for most viewing angles and for a time interval of $\sim 2 \,\text{Gyr}$ before and after core crossing depending on the mass ratio and impact parameter of the merger. On the other hand, observing a pre-merger system would show the opposite signatures because



Figure 7. Overlay of the galaxy densities as derived from the GMM models over a color scale image of the adaptively smoothed 0.2-10 keV X-ray emission. The right image shows the more compact galaxy group A and the contours are 0.17, 0.34, 0.51, 0.68, 0.85, 1.1, 1.4, 1.57, 1.64, 1.81, and 2.1 galaxies arcmin⁻². The left image shows the most spatially dispersed group B with contours <math>0.04, 0.09, 0.13, 0.17, 0.21, 0.26, 0.3, 0.34, 0.39, and 0.43.



Figure 8. 3D scattered plot of the sky position and redshift of the cluster members. The galaxies are color coded according to their velocities. In addition, we have projected the velocity histograms of the two GMM groups. Group A is shown in red and group B in blue. Finally, we also show the projected spatial density for the members of each GMM group. The contours of group A are in red and are projected to the right whereas the contours for group B are projected to the left.

the galaxies would still be clustered around their center of mass but their velocity distributions would overlap as they have the same redshift. Based on the evidence for a merger in A562 we decided to compare the data with simple N-body simulations of cluster mergers. We refer the reader to Gómez et al. (2002) for details



Figure 9. Model selection criteria AIC (solid line) and BIC (dotted line) as a function of the number of components for the sample that combines positions and velocities (3D data set).

about the simulations and scaling of the simulations with real data. We concentrated on head-on and non-head-on mergers (with impact parameters from 250 to 750 kpc) and mass ratios from 1:2 to 1:4. In order to compare the simulations to the observed velocity distribution of the galaxies it was necessary to apply a numerical scaling to the velocities of the *N*-body particles, since the model calculations were done in scale-free coordinates. We used the Kolmorov–Smirnoff (KS) test to estimate the probability that the observed galaxy velocity distribution and the velocity distribution of the *N*-body particles (sampled during a merger) are drawn from the same parent population.

Some of the results are shown in Figure 10. In this figure the vertical axis shows the initial mass of the main merging subcluster while the horizontal axis shows the time since closest core approach for a 1:4 mass ratio merger and 400 kpc impact parameter. The different symbols indicate the different viewing directions assumed. Only models with a (two-sided) KS probability for rejection of 70% or more are plotted. Overall 8700 possible models as a function of epoch (from \sim 6 to 5 Gyr with a typical timestep of ~ 0.3 Gyr) and initial main subcluster mass (from $0.7 \times 10^{15} M_{\odot}$ to $1.5 \times 10^{15} M_{\odot}$ with a typical mass spacing of $\sim 4 \times 10^{13} M_{\odot}$) were sampled for each viewing angle. Figure 11 shows the velocity distribution envelope of the models with KS probability for rejection of 70% or more and shows how these accepted models compare with the observed velocity distribution. These results demonstrate that the observed velocity distribution in A562 is consistent with the velocity distribution expected from the major non-head-on merger of two subclusters (mass ratio 1:4),



Figure 10. Allowed merger models plotted as a function of main cluster mass and time since the epoch of closest approach, based on comparing the line-of-sight velocity distributions from the observed galaxies near the center with the modeled distributions. Those models with a KS probability greater than 70% are shown; many other possible models were rejected. In this case we only analyzed non-head-on mergers with 1–4 mass ratios. The red dots show mergers with an impact parameter of 125 kpc and the blue dots show mergers with an impact parameter of 500 kpc. Moreover, we only include models with a viewing angle of 15 deg (where 0 deg corresponds to viewing along the merger axis).

close to or after the time of core crossing, with the exact epoch depending on the mass ratio and viewing geometry. In addition, Figure 12 is an example of the projected dark matter surface model for one of these accepted models that is consistent with



Figure 11. Comparison of the observed and simulated velocity histograms. This figure shows the maximum and minimum envelope of the simulated histograms (blue) from models with a KS probability greater than 0.7 (see Figure 10). The red plot shows the histogram of the observed velocities normalized to the maximum number of particles in the simulated models.

the spatial bimodality revealed by the GMM analysis. This is not an attempt to find the best model but only to explore if a non-head-on merger could provide a reasonable model for the observations. Finally, note that the WAT host could be at rest relative to the bulk of the cluster during this merger because the merger is non-head-on and it is very asymmetric (4:1 mass). The main assumption here is that the WAT galaxy probably originated in the most massive merging cluster and close to the bottom of its potential well. This assumption is supported by the GMM which allocated the WAT host to the most massive galaxy group A. Unfortunately we cannot confirm this with our *N*-body simulations because they lack the mass and spatial resolution to identify individual galaxies.

At this time, our simulations do not include gas. But we have looked at the literature to explore the properties of the cluster gas during a similar merger. We found a previous detailed hydrodynamical numerical simulation of a non-head-on merger for A754 (Roettiger et al. 1998). Figure 1 of that paper shows an X-ray emission with two elongations. The main X-ray emission is elongated in the north northeast to south southwest direction whereas there is another fainter large-scale elongation in the southeast to the northeast direction. The spatial distribution of the galaxies is also bimodal. One clump is located on top of the main X-ray emission (labeled as SE) whereas the second clump is located some 900 kpc away toward the edge of the large southeast to northwest X-ray emission (labeled NW). The most interesting characteristic is the fact that the small scale X-ray gas elongation is not parallel to the southeast to the northwest direction that connects the two galaxy clumps. The presence of two groups of galaxies aligned in a direction that is not parallel to the main X-ray elongation is also present in A562.

The hydrodynamical simulation reported by Roettiger et al. (1998; also see Henriksen & Markevitch 1996) models A754 as a post-merger non-head-on merger (impact parameter of 120 kpc) of two clusters with a mass ratio of 2.5:1. Moreover, they propose that the merger occurred close to the plane of the sky and is being observed some ~0.5 Gyr after core crossing. Thus, a similar non-head-on merger would be consistent with most of the acceptable models for A562 (see Figure 10). In addition, these hydro/*N*-body simulations provide additional information about the velocity properties of the cluster gas at different epochs. For instance, Figure 6 shows the distribution of the gas velocity some 2.75 Gyr after the moment of closest approach. This is later than most of the models that we have proposed for A562 (peak at 2 Gyr after the epoch of closest



Figure 12. Projected surface density plot for one of the simulated models (impact parameter of 500 kpc) depicted in Figure 10. In this case the merger epoch is ~0.5 Gyr after the time of closest approach. The merger started from the left and the initial direction was parallel to the *x*-axis. The projected distance between the two main clumps is ~750 kpc, which is comparable to the observed distance between the main clumps in Abel 562 of ~600 kpc. The depicted region is 4.7 Mpc × 4.7 Mpc.

approach). However, we can derive some insightful information about the kinematical properties of the X-ray gas. For instance at 0.3 Gyr the bulk flow velocity peaks at over 1800 km s^{-1} and at 2.75 Gyr it peaks at over 950 km s^{-1} . As described by Douglass et al. (2011) these are the bulk flow magnitudes needed to bend the radio jets and form the WAT.

4.1. WATs as Wind Socks

In the previous sections we have described a merger model that can explain the main bending observed in the tails of the WAT radio source. However, this source shows other morphological features whose origins are still unexplained. For instance, the jets in 0647+693 show several minor bends (i.e., N1, N2, and N3 in Figure 11 of Douglass et al. 2011) and changes in direction. As shown by Roettiger et al. (1998) a non-head-on merger induces significant angular momentum to the cluster gas that manifests itself as rotations and eddies. Therefore, we are wondering if these bends and twists could be produced by the interaction between the jets and the different types of gas flows stirred by the merger. In order to make a qualitative assessment, in Figure 13 we have overlaid the radio image of the WAT on the hydro/N-body velocity fields produced by Roettiger et al. (1998) for the A754 merger at 0.5 Gyr after the epoch of closest approach. It is tantalizing to see that the N1, N2, and N3 bends can be naturally caused by ram pressure produced by the rotating and turbulent gas. This is only a qualitative comparison that can motivate further studies of the pressure balances along the jets and comparison with the velocity fields produced by hydrodynamical cluster merger simulations. Could this suggest that WAT radio sources with severely distorted tails (i.e., A562) are only present in nonhead-on mergers whereas bent radio sources with symmetric



Figure 13. Overlay of a 1.4 GHz VLA radio map of the A562 WAT (from E. M. Douglass 2020, private communication) over the velocity field predicted by the A754 simulation (adapted from Roettiger et al. 1998). The contours show the synthetic X-ray emission as predicted for a non-head-on merger seen some 0.25 Gyr after the epoch of closest approach. Note that the arrows represent the gas velocity and the maximum value is 1850 km s⁻¹ in a ~2 Mpc × 2 Mpc. We can see that the southern jet is oriented within a region free from large eddies whereas the northern jet encounters a fast rotating flow of gas and other eddies that could be responsible for the observed bends.

tails (e.g., A2634 as described in Pinkney et al. 1993) are mostly present in head-on mergers? We plan to further explore the potential of the radio morphology as a merger diagnostics on larger samples of WAT clusters with high spatial resolution VLA maps. Finally, we look forward to map out cluster gas velocities with the upcoming X-ray Imaging and Spectroscopy Mission (XRISM) and compare them with the WAT geometry.

5. Conclusions

We measured new redshifts for 102 galaxies in the vicinity of A562 with the GMOS-N instrument mounted on the Gemini North telescope. After combining with data in the literature, we obtained a sample of 76 likely cluster member galaxies. We concentrate our study of the cluster's kinematics on these galaxies.

We calculated a new robust redshift for this cluster of 0.1088 and a velocity dispersion of $919 \pm 116 \text{ km s}^{-1}$. Moreover, we found a negligible peculiar velocity for the WAT galaxy which is typical of these radio sources.

We find evidence for kinematic structure and non-Gaussianity in the velocity data of these galaxies. The velocity distribution is asymmetric and shows kurtosis. Next, we find some evidence of substructure as quantified by the Lee statistics on the sample of color-selected galaxies. Even if our 3D statistical tests do not find evidence for substructure, we find interesting results when we use the Gaussian mixture modeling on the data. The GMM technique used as a density estimator splits the data in two statistically significant groups.

Motivated by these results and the analysis of Chandra X-ray data from the literature, we compared our spatial and velocity data with simple *N*-body simulations of non-head-on cluster mergers. We find that the velocity distributions produced by the merger of two subclusters with a mass ratio of about of 1:4 near the time of core crossing and occurring close to the plane of the sky are consistent with the observed velocity distribution. In addition, near the epoch of core crossing the 1:4 merger

produces a qualitatively similar X-ray spatial distribution as the one seen in A562.

In summary, our kinematical study supports the view that A562 is a non-head-on merging cluster and that the WAT galaxy does not have a significant peculiar velocity. These findings support the hypothesis that the WAT bending is produced by the interaction of the radio jets with the bulk flow motions of gas produced by a merger. Further insights into the nature of this WAT and into the process of cluster merging should be forthcoming with the data expected from the new generation of X-ray missions.

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