THE DYNAMICS OF A2125

NEAL A. MILLER
NASA Goddard Space Flight Center, Laboratory for Astronomy and Solar Physics, Code 681, Greenbelt, MD 20771; nmiller@stis.gsfc.nasa.gov

FRAZER N. OWEN
National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801; fowen@aoc.nrao.edu

JOHN M. HILL
Large Binocular Telescope Observatory, University of Arizona, Tucson, AZ 85721; jhill@as.arizona.edu

WILLIAM C. KEEL
Department of Physics and Astronomy, University of Alabama, Box 870324, 206 Gallalee Hall, Tuscaloosa, AL 35487; keel@bildad.astr.ua.edu

MICHAEL J. LEDLOW
Gemini Observatory, c/o AURA, Casilla 603, La Serena, Chile; mledlow@gemini.edu

AND

WILLIAM R. OEGERLE
NASA Goddard Space Flight Center, Laboratory for Astronomy and Solar Physics, Code 680, Greenbelt, MD 20771; william.r.oegerle@nasa.gov

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ABSTRACT

We present 371 galaxy velocities in the field of the very rich cluster A2125 (z ≈ 0.25). These were determined using optical spectroscopy collected over several years from both the WIYN 3.5 m telescope and NOAO Mayall 4 m telescope. Prior studies at a variety of wavelengths (radio, optical, and X-ray) have indicated that A2125 is a likely cluster-cluster merger, a scenario that we are able to test using our large velocity database. We identified 224 cluster galaxies, which were subjected to a broad range of statistical tests using both positional and velocity information to evaluate the cluster dynamics and substructure. The tests confirmed the presence of substructures within the A2125 system at high significance, demonstrating that A2125 is a complex dynamical system. Comparison of the test results with existing simulations strengthens the merger hypothesis and provides clues about the merger geometry and stage. The merger model for the system can reconcile A2125’s low X-ray temperature and luminosity with its apparently high richness and might also explain A2125’s high fraction of active galaxies identified in prior radio and optical studies.

Subject headings: galaxies: clusters: individual (A2125) — galaxies: evolution — galaxies: kinematics and dynamics

Online material: machine-readable tables

1. INTRODUCTION

A2125 is a very rich cluster of galaxies (richness class 4; Abell et al. 1989) found at intermediate redshift (z ≈ 0.25). It was identified as an active cluster in the Butcher & Oemler (1984) study, with a noted blue fraction of 0.19. This would suggest an increase in the star formation of A2125 galaxies relative to those found in low-redshift clusters, which typically have blue fractions ≈ 0.03. Considerable effort has been expended to confirm this suggestion via radio continuum observations (Dwarakanath & Owen 1999; F. N. Owen et al. 2004, in preparation). The radio continuum emission at 20 cm for normal and starbursting spirals is strongly correlated with far-infrared (FIR) emission (e.g., Helou et al. 1985; Yun et al. 2001). It is believed that the source of this correlation is massive stars, whose supernovae accelerate electrons that radiate synchrotron emission in galactic magnetic fields (for a review see Condon 1992). The same massive stars are the dominant source of FIR emission as they heat gas and dust in their parent molecular clouds. Indeed, analogous to the photometric results, A2125 was shown to have a large radio galaxy fraction implying an elevated level of star formation (Dwarakanath & Owen 1999). A companion study adding optical spectroscopy confirmed that the identified radio galaxies were cluster members and argued that the high blue/radio fraction was due to the dynamical state of A2125, which appears to be that of a cluster-cluster merger (Owen et al. 1999). Additional radio and optical observations have extended this result to much lower luminosities (F. N. Owen et al. 2004, in preparation), further underscoring the high level of activity in A2125. This activity includes a high fraction of active galactic nuclei (AGNs), as well as an excess of star-forming galaxies.

The interpretation of A2125 as a cluster-cluster merger is based on both its galaxy distribution (Owen et al. 1999) and its
X-ray structure (Wang et al. 1997, 2004). The Wang et al. (1997) X-ray observations were performed with the ROSAT PSPC and indicated a complex environment. This impression was strengthened by recent Chandra observations in Wang et al. (2004). Multiple peaks in the X-ray emission were identified, in addition to larger scale diffuse emission. The emission coinciding with the core of A2125 was shown to have an ellipticity of 0.25–0.33 (Chandra results, 90% confidence range) and a north-to-east position angle between 115° and 127°. The X-ray emission corresponding to the core of A2125 was also noted to be clumpy. In conjunction with the low measured temperature of 3.2 keV, these findings indicated that A2125 was a dynamically complex system. Additional peaks in the X-ray emission outside the main body of A2125 were observed to the north, along with more diffuse extended emission to the southwest. This diffuse emission is of cooler temperature (~1 keV) and correlates with concentrations of spiral galaxies. It might thereby represent diffuse intergalactic gas associated with large-scale hierarchical structure formation. In total, the X-ray observations led to the interpretation of the entire system as a supercluster over 7 Mpc in extent. Interestingly, the X-ray ellipticity of the main body of A2125 was roughly perpendicular to the overall superstructure, leading the authors to suggest that the core of A2125 represented “an initial coalescence of subunits of comparable mass.”

Consequently, there is much interest in a detailed dynamical assessment of A2125. The prior studies lacked large numbers of measured galaxy velocities with which to assess possible substructures and the overall merger environment, and we have undertaken a broad campaign of optical spectroscopy to remedy this. In this paper we report over 450 new velocity measurements of 371 galaxies in the field of A2125. The optical spectra were collected using several instruments, including the Hydra multifiber spectrograph on the WIYN 3.5 m telescope, multislit spectra collected using the Mayall 4 m telescope, and long-slit spectra taken with the RC spectrograph at the Mayall telescope (previously published in Owen et al. 1999). The galaxy velocities and positions were subjected to a collection of statistical tests in order to identify substructure in A2125 and quantify its significance. A2125 is shown to be a highly complex system, rich in substructure. Comparison of the test results with those determined for simulations indicates that the data are consistent with models of cluster-cluster mergers. In this interpretation, A2125 is viewed along an axis offset slightly from the merger axis and at an epoch within a few hundred million years of the time when the cores of the merging clusters have crossed.

We begin with a description of the spectroscopy database in § 2. Analysis of the resulting velocities is presented in § 3. In § 4 we assess the merger hypothesis by comparing the substructure tests with computer models and view the results in light of X-ray and radio investigations of the cluster. Our conclusions are briefly summarized in § 5. We have adopted the WMAP cosmology of $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_r = 0.73$ for all distance-dependent calculations, meaning that 1” corresponds to about 3.8 kpc at A2125. The classical Abell radius ($R_A \equiv 1.7/z$; Abell 1958) for the cluster is thereby 1.59 Mpc.

2. OBSERVATIONS AND DATA REDUCTIONS

2.1. Multifiber Spectroscopy Using WIYN with Hydra

2.1.1. 1996 Observations

Observations of A2125 were performed by W. R. O. and J. M. H. using the Hydra multifiber spectrograph on the WIYN 3.5 m telescope during a pair of observing runs in 1996. Three fiber configurations were observed during 1996 April 16–18, and a fourth was observed during 1996 May 20–22. Each run used the blue fibers (3”) and a 400 line mm$^{-1}$ grating blazed at 4000 Å. This produced wavelength coverage from about 4300 to 7500 Å at a resolution of 7 Å. Each configuration was observed multiple times to reject cosmic rays and produce high signal-to-noise spectra. Total exposure times varied depending on observing conditions but ranged from 3 to 5 hr (see the summary in Table 1).

Calibration frames were taken using standard methods. At least 20 bias frames were collected on each night, as well as at least three flat fields per fiber configuration. Wavelength calibration was achieved via observation of CuAr lamps, performed both before and after science observations of a given fiber configuration. The wavelength solutions typically produced an rms residual less than 0.15 Å as determined from about 45 lines. Of the 96 available fibers per configuration, typically around 30 were assigned to random locations to produce a good-quality sky spectrum.

Each science exposure was reduced individually, with the set of exposures for a given fiber configuration then combined to produce the final spectra. The standard IRAF tasks within the NOAO HYDRA package were used to produce the final wavelength-calibrated, sky-subtracted spectra for each exposure. The set of exposures corresponding to a given fiber configuration were then median combined after weighting by their modes (as defined in a region between 5000 and 5500 Å, chosen to avoid strong emission and absorption features in cluster galaxies).

Measurement of galaxy velocities proceeded along one of two paths. First, the spectra were cross-correlated against a collection of velocity standards (using the IRAF RV package; see Tonry & Davis 1979). These included spectra of the...
nearby galaxies NGC 3379 (assumed velocity 922 km s$^{-1}$), NGC 7331 (819 km s$^{-1}$), M31 (−297 km s$^{-1}$), M32 (−200 km s$^{-1}$), and a bright elliptical in A779 (6877 km s$^{-1}$), determined from cross-correlation with the other templates and observed multiple times, plus standard stars HD 52071 (94.7 km s$^{-1}$) and BD +25°3190 (−49.5 km s$^{-1}$). The velocity standard spectra (hereafter “template” spectra) were collected over several years using a variety of spectrographs at resolutions comparable to the present observations. In total, the template list included 22 spectra. Cross-correlation velocities for each observed galaxy were then determined from the velocities derived using each of the 22 templates. First, the average of the velocities was determined (weighted by the $R$-values, where $R$ is a measure of the goodness of fit defined as the ratio of the height of the peak in the cross-correlation to that of the average peak; see Tonry & Davis 1979) and outliers were clipped ($±3σ$). The dispersion in the remaining velocities was required to be less than 115 km s$^{-1}$, and we also required that the $R$-values were greater than 2.5. Finally, we required that at least 60% of the templates produced acceptable velocities given these restrictions. Initial errors were based on the weighted average $R$-value, such that the error equals 280(1 + $R$)$^{-1}$ km s$^{-1}$ (see Tonry & Davis 1979; Hill & Oegerle 1998). The final error represents this value added in quadrature with an additional uncertainty of 40 km s$^{-1}$ (see § 2.3).

The spectra were also inspected by eye by two of us (N. A. M. and F. N. O.) independently to confirm the results. In addition to confirmation of cross-correlation velocities, many emission-line spectra were identified. For these galaxies, we fitted Gaussian profiles to up to 11 emission lines typically observed in star-forming galaxies and AGNs: [O ii] $λ3727$, H$γ$ $λ4340$, H$β$ $λ4861$, [O iii] $λ4959$, [O iii] $λ5007$, [N ii] $λ6583$, [S ii] $λ6716$, and [S ii] $λ6731$. Velocities were determined for each detected line, and a net galaxy velocity was derived from these via a simple average (requiring that at least two emission lines be measured). The heliocentric correction was then applied to arrive at the final emission-line velocity. To evaluate the errors, we determined the dispersion in the line measurements for each galaxy. As this quantity is somewhat dependent on the number of measured lines (e.g., a galaxy with only two measured lines may have a much lower associated dispersion than a strong emission-line galaxy with 10 lines), we calculated the average dispersion over all emission-line galaxies, arriving at a value of 39 km s$^{-1}$. This represents the combination of various error terms including errors in measurement of line positions, wavelength calibration errors (which should be about 10 km s$^{-1}$ based on the rms residual obtained from the wavelength solution), and gas motions within the galaxies. We therefore adopted 40 km s$^{-1}$ as the error in our velocities determined from emission lines.

Final velocities were then adopted based on the cross-correlation and emission-line values. For galaxies proving to be cluster members (see below), these observed heliocentric corrected velocities ($cz$) may be found in Table 2. For non-cluster members (foreground and background galaxies and quasars), the heliocentric redshifts may be found in Table 3. In general, we used the emission-line values whenever they were available. For several cases in which the lines were weak or noisy, we instead used the cross-correlation values. These are marked in Tables 2 and 3 with the noted emission lines offset in parentheses. Note that in nearly all cases in which both an emission-line and a cross-correlation velocity were available, the two velocities were consistent within about 150 km s$^{-1}$. A small number of cross-correlation velocities with low $R$-value were adopted in specific cases in which a single emission-line measurement (usually [O ii]) confirmed the cross-correlation value.

### 2.1.2. 2000 Observations

Additional spectroscopy using Hydra on the WIYN telescope was performed in the queue observing mode over several nights from 2000 March through May (see Table 1). These used the red cables (2$^{''}$ fibers) and the 316 line mm$^{-1}$ gratings blazed at 7$''$, providing wavelength coverage from $\sim$4300 to $\sim$9150 Å at $\sim$6 Å resolution. Three fiber configurations each consisting of $\sim$65 target galaxies were observed in five or six exposures each of 2800 s duration. Most of the remaining fibers were used to create a sky spectrum for data reduction. In addition to the science exposures, CuAr wavelength calibration frames were interspersed along with observations of velocity and spectrophotometric standards. Zeros, dome flats, and sky flats were also obtained on each night.

The data reduction and determination of velocities were similar to those for the 1996 data. The procedure for determining the cross-correlation velocities differed slightly from that outlined above. Five template spectra, corresponding to M31, M32, NGC 3779, NGC 7331, and HD 132737 (assumed velocity of $\sim$24 km s$^{-1}$), were each run interactively with the individual spectra. Regions for the correlations were chosen on a case-by-case basis to emphasize stronger absorption features such as the 4000 Å break, with the best fit (i.e., highest $R$-value) being adopted as the velocity for a given galaxy. Velocity errors were then determined in the same manner as for the 1996 WIYN data.

### 2.2. Multislit Spectroscopy at 4 m Mayall Telescope

The 4 m Mayall Telescope was used for spectroscopic observations of A2125 by W. C. K., F. N. O., and M. J. L. on three nights from 1998 May 27 to 29 (Table 1). These observations were performed using 13 custom-made multislit masks, each consisting of between eight and 13 2$''$5 slits centered on target galaxies. The primary motivation of these observations was to obtain spectra of galaxies with radio emission (see F. N. Owen et al. 2004, in preparation), with additional slits placed on galaxies with $m_B \leq 20$. The RC
spectrograph was used along with grating KPC-10A (316 lines mm\(^{-1}\), blazed at 4000 Å), providing a resolution of ~7 Å and coverage from 4000 past 9200 Å. Each mask was observed for a total exposure time of 1 hr, split into two 30 minute exposures to facilitate rejection of cosmic rays. Flux calibration was achieved through observation of standard stars through slits of the same width, including standard stars viewed through slits from the actual science multislit masks. Data reduction and determination of galaxy velocities were achieved in the same manner as that applied to the 2000 WIYN data.

### 2.3. Additional Data and Combination of Velocities

In addition to the velocity data described above, we have included the velocity data from Owen et al. (1999). These were obtained using a long slit on the KPNO Mayall 4 m telescope with the RC spectrograph. Most of these galaxies have been reobserved by at least one of the above spectroscopic campaigns, meaning that only three velocities (two of which are cluster galaxies) are added to the data from this source. In total, there are 374 galaxies in our database, including 371 listed in Tables 2 and 3. Many galaxies have spectroscopy results from multiple observing runs, meaning that the two tables contain a total of 454 entries.

Visual inspection of the spectra also identified a handful of quasars. These have been noted in Table 3, along with their redshifts and comments indicating the emission features upon which such measurements are based. The broad emission lines make precise determination of redshifts difficult, so we have arbitrarily assigned an error of \( \Delta z = 0.001 \) (300 km s\(^{-1}\)) to these redshifts.

With many galaxies being the targets of multiple observing runs, we explored possible offsets in our derived velocities. We adopted the 1996 WIYN Hydra observations as a benchmark and compared the velocities obtained from these observations with the velocities obtained from the other observations (the 2000 WIYN Hydra observations and the 1998 Mayall observations). These comparisons were further split into velocities determined by cross-correlation and velocities determined by locations of emission lines. The emission-line velocities in common were consistent for each data set (mean difference between 2000 WIYN data and 1996 WIYN data of \(-7\) km s\(^{-1}\) for 17 galaxies, mean difference between 1998 Mayall data and 1996 WIYN data of 12 km s\(^{-1}\) for 10 galaxies). The velocities determined via cross-correlation were also generally consistent, with the 2000 WIYN velocities an average of 51 km s\(^{-1}\) greater than the 1996 WIYN velocities (17 objects in common) and the 1998 Mayall velocities an average of 15 km s\(^{-1}\) less than the 1996 WIYN velocities (based on 24 common objects). Differences as small as these can easily result from sampling different portions of the target galaxies through combinations of astrometry, pointing, and aperture size.

We further tested possible offsets using velocity standard star observations. Typically, a velocity standard star was observed on each night of the observing runs. Velocities for these standard stars were determined via cross-correlation using the various template velocity standard spectra. The mean velocity for a given standard star, determined from the full set of template spectra, was usually within 15 km s\(^{-1}\) of the cataloged velocity. The full spread in velocities determined from the various templates was \(\leq 70\) km s\(^{-1}\), with a typical dispersion around 20 km s\(^{-1}\). Rather than apply any zero-point shifts to velocities determined from data collected on specific nights and observing runs (none of which would be statistically significant), we have elected to include an additional error of 40 km s\(^{-1}\) (added in quadrature) to the reported galaxy velocities.

In compiling our final velocity list for dynamical analysis, we prioritized the observations as follows. If a velocity obtained from the 1996 WIYN observations was available for a given galaxy, it was adopted. If a galaxy was unobserved by the 1996 WIYN observations, we used its 2000 WIYN velocity (if available), followed by any 1998 Mayall velocity and lastly by any Owen et al. (1999) velocity. This hierarchy is largely governed by numbers and is meant to maintain as consistent a velocity database as possible.

With spectroscopy data coming from four separate sources, it is useful to investigate possible bias in our sampling of cluster galaxies (e.g., obtaining relatively more velocities for some portions of the cluster than for others). Fortunately, this is mitigated by the large (60’ diameter) field of view of WIYN+Hydra, which equates to nearly 7 Mpc at the redshift of the cluster. In Figure 1 we plot the positions of all galaxies for which we have spectra. It can be seen that our spatial sampling is relatively uniform, particularly by noting the distribution of background galaxies (open triangles in the figure). Optical images of the cluster, particularly those with high resolution, often reveal tight groupings of galaxies (F. N. Owen et al. 2004, in preparation). Limitations on fiber spacing with Hydra (37") mean that any single fiber configuration will miss some galaxies. However, since seven different fiber configurations were observed (four in 1996, three in 2000), this effect is lessened. Overall, the net effect of missing a few
galaxies in tight groupings should be minimal in performing the dynamical assessments. In fact, missing spectra for some galaxies in tight groups would result in less pronounced evidence for substructure than is actually present.

3. ANALYSIS: TESTS OF SUBSTRUCTURE

A histogram of the velocity data is presented in Figure 2. A2125 is easily seen as the single strong peak in the velocity distribution. In all, there are 224 cluster galaxies as identified via 3σ clipping of the velocity data (Yahill & Vidal 1977). The calculated biweight location and scale (see Beers et al. 1990) are $73,897 \pm 74$ ($z = 0.2465$) and $1113^{+37}_{-49}$ km s$^{-1}$, respectively. These numbers have been corrected for measurement errors (see Danese et al. 1980), and the dispersion was calculated from relativistically corrected velocities (which we use for all subsequent dynamics calculations). We adopt the biweight location as our cluster systemic velocity and the biweight scale as our cluster velocity dispersion for the remainder of this discussion. Note that the “nonrobust” calculations of the mean and dispersion yield $73,995 \pm 96$ and $1150^{+51}_{-59}$ km s$^{-1}$, similar to the robust quantities.

The 224 cluster galaxies were subjected to a battery of statistical tests to evaluate potential substructure. These included tests performed exclusively on the velocity data (the “ROSTAT” package of Beers et al. 1990) and tests on the galaxy positional data both with and without velocity information (for a complete listing and description of all tests, see Pinkney et al. 1996, hereafter P96). The advantages to using a battery of statistical tests are noted in P96. Essentially, each test provides a different perspective on the dynamical state of the cluster, and taken collectively they often complement one another. Understanding a set of results is aided greatly by comparison with numerous N-body simulations.

The tests performed exclusively on the velocity data (one-dimensional tests) generally compare the distribution to that of a Gaussian and are presented in Table 4. Since the computational algorithms in the ROSTAT package that are used to determine the significance for the $B_1$ and $B_2$ statistics ($B_1$ and $B_2$ are the canonical estimators of skewness and kurtosis and represent the third and fourth moments of the velocity distribution) fail for large $N$, we have estimated their significance via 40 randomly drawn subsets (with $N = 150$) of the full data set. Most of the one-dimensional tests indicated significant non-Gaussian behavior of the velocity histogram. Qualitatively, this may be understood by inspection of Figure 2. In particular, the cluster histogram has a “tail” at higher velocity. This produces significant skewness to the distribution but does not make it overly kurtotic (e.g., the cluster distribution is more skewed than a Gaussian at better than 95% confidence based on the $B_1$ statistic, yet consistent with a Gaussian in the sense of kurtosis based on the $B_2$ statistic). Consistent with the visual interpretation, combinations of the statistics indicate that the distribution has more counts to the higher velocity side of the mean and similarly that the long tail identified by the tests resides on this side.

Similarly, tests performed on the positional data both with and without the associated velocities produced strong evidence for substructure. Table 5 presents the nine tests performed and their results. With the exceptions of the angular separation test (AST; West et al. 1988) and the $\epsilon$ test (Bird 1993), all indicate highly significant substructure (at $\geq 99.7\%$ confidence, as determined via 1000 Monte Carlo simulations). As an example, in Figure 3 we present the graphical representation of the $\Delta$ test (Dressler & Shectman 1988). This test calculates local deviations from the systemic velocity ($v_{sys}$) and dispersion ($\sigma$) of the entire cluster:

$$\delta_i^2 = \frac{N}{\sigma^2} \left[ \left( v_{local} - v_{sys} \right)^2 + \left( \sigma_{local} - \sigma \right)^2 \right].$$  (1)

Here $N$ is the number of galaxies that defines the local environment around galaxy $i$, taken to be $N = 11$ in the original
TABLE 4
NORMALITY TESTS FOR A2125

| Test        | Statistic | Significance |
|-------------|-----------|--------------|
| A           | 0.784     |              |
| U           | 4.840     | 0.000        |
| W           | 0.965     | 0.001        |
| B1          | 0.334     | 0.045        |
| B2          | 2.762     | 0.324        |
| B1B2 Omni   | 3.343     | 0.184        |
| I           | 0.980     | 0.150        |
| KS          | 1.017     | 0.025        |
| V           | 1.714     | 0.010        |
| W2          | 0.214     | 0.004        |
| U2          | 0.185     | 0.005        |
| A2          | 1.342     | 0.002        |
| DIP         | 0.017     | 0.030        |
| AI          | 0.109     |              |
| TI          | 1.252     |              |

Notes.—The significance represents the probability that the
distribution is consistent with a Gaussian. Thus, a low number
indicates likely non-Gaussian behavior.

\(^a\) The significance for these tests cannot be determined analyti-
cally. For comparison purposes, the AI test statistic for a
Gaussian is equal to 0.0 and for TI it is equal to 1.0. See Bird &
Beers (1993) for more information on the AI and TI tests.

\(^b\) Based on the results for 40 \(N = 150\) data sets drawn at
random from the full \(N = 224\) set of velocities (see text). The
dispersions in these values (i.e., the biweight scales) were 0.041
for B1, 0.122 for B2, and 0.135 for the B1B2 Omni test. In each
case, the test statistic derived from the 40 \(N = 150\) data sets was
nearly identical to that derived for the full \(N = 224\) data.

\(^c\) This is the default value for a nonsignificant deviation for
the implementation of this test (see P96). Note that all 40
\(N = 150\) randomly drawn subsets of the full velocity list yielded
significance values of 0.15, indicating no significant deviation
from a Gaussian. The I test is normally evaluated and compared
to \(I_{90}\) to determine whether a distribution is non-Gaussian; dis-
tributions are considered consistent with a Gaussian if \(I < I_{90}\).
For the A2125 velocities, \(I_{90} = 1.024\).

\(^d\) The significance values for this implementation of the KS
test are restricted to 0.25, 0.10, 0.05, 0.025, and 0.01.
Using the 40 randomly drawn \(N = 150\) subsets, the robust mean
significance is 0.055 with a dispersion of 0.086.

TABLE 5
MULTIDIMENSIONAL SUBSTRUCTURE TESTS FOR A2125

| Test        | Dimensionality | Significance | Reference |
|-------------|----------------|--------------|-----------|
| Fourier elongation | 2D             | 0.000        | 1         |
| \(\beta\)    | 2D             | 0.000        | 2         |
| Angular separation | 2D             | 0.063        | 2         |
| Lee         | 2D             | 0.001        | 3         |
| Lee         | 3D             | 0.001        | 1         |
| \(\Delta\)   | 3D             | 0.003        | 4         |
| \(\epsilon\) | 3D             | 0.130        | 5         |
| \(\alpha\)   | 3D             | 0.000        | 6         |
| \(\alpha\)   | 3D             | 0.000        | 1         |

Notes.—Implementations of all tests are described in P96 and generally
follow the prescriptions for the tests as set forth by the original authors. One
minor exception is the number of nearest neighbors used, which was frequently
10 in the original tests (e.g., the \(\Delta\) and \(\alpha\) tests) but set to \(N^{1/2}\) in the P96 code
[hence, \((224)^{1/2} = 14.97\) and the tests used the 15 nearest neighbors]. Sign-
ificance values are determined from 1000 Monte Carlo simulations.

References.—(1) P96; (2) West et al. 1988; (3) Fitchett 1988; (4) Dressler
& Shectman 1988; (5) Bird 1993; (6) West & Bothun 1990.

Fig. 3.—Dressler-Sheetman plot for A2125. Each galaxy is plotted by a
circle with the diameter of the circle proportional to \(e^\phi\).

In an attempt to identify substructures and determine which
galaxies compose these substructures, we applied the KMM
algorithm (see Ashman et al. 1994). This algorithm divides a
system into a specified number of components and calculates
the Gaussian distance (using both positions and velocities)
of each galaxy to each component.\(^3\) The galaxies are assigned
to their nearest component, new means and dispersions for
the positions and velocities of each component are calculated,
and the procedure is repeated. The algorithm converges when
the assignments are stable. In addition to the assignments,
the probability that a given assignment is accurate may be as-
essed through the Gaussian distances of that galaxy to each component.
For example, if a galaxy were equidistant to two
components, its assignment would only imply 50% confi-
dence. It should be stressed that the algorithm is statistical and
does not necessarily imply association with a real physical
substructure. Any number of components may be specified by the user, and the algorithm will attempt to apportion the data into those components. In some cases, the algorithm either will not converge or will remove nearly all galaxies from a given component, indicating that the specified component is not viable.

Based on the observation that the velocity histogram had a long tail at higher velocities, our first KMM run divided the cluster into two components, a primary and a higher velocity subcluster to the southwest. Noting the multiple regions for substructure in the graphical representation of the Δ test (Fig. 3), we proceeded to a three-component fit. This fit kept the higher velocity subcluster to the southwest largely intact and split off a lower velocity system to the northeast. This same general impression is obtained from an adaptively smoothed distribution of the galaxy surface density, as shown in Figure 5 of Owen et al. (1999). Details of these KMM runs are provided in Tables 6 and 7, and the results of the three-component fit are depicted in Figures 4 and 5.

A slight digression on the validity of the KMM assignments is in order. The original astronomical application of KMM by Ashman et al. (1994) was to detect bimodality in univariate data sets. For this purpose, and assuming that the data are split into two components of equal dispersion but different mean, the authors found KMM to be relatively insensitive to input parameters. As might be expected, we have found through extensive testing that addition of variables largely removes this independence on input conditions. Clearly, adding two additional variables (for position) and relaxing the constraint that different components have common dispersions in a given variable expands the set of possible solutions. For example, with carefully chosen input parameters we were able to produce a two-component fit that largely ignored velocity and separated the cluster into a main component and a southwest clump, as well as a three-component fit that largely ignored position and subdivided the higher velocity galaxies into two components. The merits of these various solutions are difficult to debate; Ashman et al. (1994) note that the significance at which an additional substructure improves the fit to the data is difficult to determine in all but the fairly simple case of a single variable decomposed into two components of equal dispersion but different mean. It is largely for these reasons that we did not extend the KMM analysis to more than three components. We note here that other solutions exist, but the two we discuss were driven by the substructure test results and in particular by the locations of substructure indicated by the Δ test (Fig. 3).

The KMM assignments enable us to revisit Figure 3, the Dressler-Shectman bubble plot (refer also to Fig. 4). Three regions of possible substructure are identified from the plot as collections of larger circles: one to the northeast, one to the southwest, and one slightly north of the cluster core. These may be caused either by groupings of galaxies at a velocity differing from the cluster as a whole or by groupings of galaxies with local dispersions differing from the cluster as a whole (refer to eq. [1]). The possible northeast substructure has larger δ-values primarily because its galaxies are at a lower velocity than the cluster. This corresponds to the lower velocity component identified in the KMM runs fitting more than two substructures. The possible southwest substructure has larger δ-values because (1) its galaxies have a higher local systemic velocity than the remainder of the cluster and (2) the higher velocity galaxies are seen in projection with galaxies at the same general velocity as the cluster, thus increasing the velocity dispersion among nearest neighbors (in particular, note the concentration of higher velocity galaxies to the southwest of the main southwest clump). This region corresponds to the higher velocity component identified in the KMM runs. Finally, the higher local δ-values just to the north of the cluster core are the result of large local velocity dispersion. This is

| Fitted Components | Component 1 | Component 2 | Component 3 |
|-------------------|-------------|-------------|-------------|
|                   | C_{R1} (km s\(^{-1}\)) | S_{R1} (km s\(^{-1}\)) | N | C_{R2} (km s\(^{-1}\)) | S_{R2} (km s\(^{-1}\)) | N | C_{R3} (km s\(^{-1}\)) | S_{R3} (km s\(^{-1}\)) | N |
| 1…………………..  | 224 | 73897 | 1113 | … | … | … | … | … | … |
| 2…………………..  | 170 | 73425 | 712 | 54 | 75970 | 603 | … | … | … |
| 3…………………..  | 136 | 73656 | 479 | 58 | 75889 | 623 | 30 | 71926 | 362 |

Note.—C_{R} and S_{R} refer to the robust estimates of the mean and dispersion for each fitted component.

| Fitted Components | Component 1 | Component 2 | Component 3 |
|-------------------|-------------|-------------|-------------|
|                   | R.A. (J2000.0) | Decl. (J2000.0) | R.A. (J2000.0) | Decl. (J2000.0) | R.A. (J2000.0) | Decl. (J2000.0) |
| 1…………………..  | 15 40 52 | 66 15 39 | … | … | … | … |
| 2…………………..  | 15 40 53 | 66 16 23 | 15 40 50 | 66 13 18 | … | … |
| 3…………………..  | 15 40 43 | 66 15 30 | 15 40 53 | 66 13 39 | 15 41 35 | 66 19 27 |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Coordinates presented refer to the mean centers for each component. The errors in these means range from about one to several arcminutes.
caused by the superposition of galaxies from the low-velocity substructure, the high-velocity substructure, and the main body of the cluster.

4. DISCUSSION

4.1. The Dynamical State of A2125

The above analysis indicates that A2125 possesses very strong evidence for substructure. What is the cause of this behavior? There are several possible interpretations. It is possible that we are simply viewing a projection of multiple clusters. The velocity separation of the main cluster and the higher velocity system implies a physical separation of $\approx 45$ Mpc, assuming that the difference is simply due to the Hubble flow. Their close alignment along the line of sight would then be fairly remarkable. Bahcall et al. (2003) used early Sloan Digital Sky Survey data to compile a cluster catalog out to $z = 0$ and from these data determined an estimate of the space density of galaxy clusters. Should clusters be distributed randomly, this space density implies that the probability of any two clusters being seen as a single cluster or group: it is too diffuse to be a virialized cluster (and is composed primarily of spiral galaxies), and although its X-ray temperature ($\approx 1$ keV) is representative of groups, its luminosity (over $10^{43}$ ergs s$^{-1}$) is in excess of typical group luminosities by an order of magnitude. Our velocity data also indicate a much higher dispersion than would be expected for a single poor cluster or group: it is too diffuse to be a virialized cluster (and is composed primarily of spiral galaxies), and although its X-ray temperature ($\approx 1$ keV) is representative of groups, its luminosity (over $10^{43}$ ergs s$^{-1}$) is in excess of typical group luminosities by an order of magnitude. Our velocity data also indicate a much higher dispersion than would be expected for a single poor cluster or group and similarly that the velocities are poorly fitted by a Gaussian (Fig. 5, although the Gaussian hypothesis for this component cannot be rejected via either the $I$ or KS tests). Thus, these X-ray papers favor that the diffuse X-ray emission to the southwest arises from hot intergalactic gas in a hierarchical structure including multiple groups. Presumably, this structure is oriented roughly along our line of sight and connects to the core of A2125.

Another possibility is that we are witnessing a cluster-cluster merger. This interpretation is based largely on comparison of the substructure test results with the $N$-body simulations of cluster-cluster mergers presented by P96. In general, the one-dimensional tests (i.e., those performed using only the galaxy velocities) are excellent indicators of mergers viewed near core passage when the relative velocity between the merging partners is greatest. Of course, this requires that the merger not be viewed orthogonal to the merger axis. Conversely, the two-dimensional (positions only) tests perform best at early epochs of mergers and when the system is viewed orthogonal to the merger axis, thereby maximizing the positional separation of the merging partners. The three-dimensional tests combine the strengths and weaknesses of their lower dimensional counterparts.

Such consistently strong indications of substructure as are found in A2125 (refer to Table 5) are fairly rare in the sim-
ulations. Even so, the results are generally consistent with either of two possibilities. The first is the earlier stages of a merger (up to 2 Gyr prior to core passage) in which the positional separation of the two components is large and consequently the system is viewed closer to orthogonal to the merger axis. The second possibility is a merger seen near the epoch when the cores of the respective clusters have become coincident and with a viewing angle more closely aligned with the merger axis (within about 30°). Since the latter possibility is the same as that obtained from the one-dimensional substructure tests, this scenario best matches the A2125 data. It is also interesting to note that the two multidimensional tests that do not suggest overly strong evidence for a merger are the two least sensitive tests identified by the simulations. These are the AST (West et al. 1988) and the $\epsilon$ test (Bird 1993). The AST looks for substructure in the form of small angular separations where the angle between any two galaxies is defined using the cluster centroid as the vertex. It therefore performs best when subclusters are well separated, a condition that fails around the time of core passage or if the system is viewed along the merger axis. The $\epsilon$ test calculates the projected mass estimator in the vicinity of galaxies using their nearest neighbors. Regions of substructure have lower projected mass estimates than the global mass estimate, and the significance of this deviation is tested via Monte Carlo shuffles of the data. Although the $\epsilon$ test is sensitive to mergers, it is most sensitive for times well after core passage (P96).

If the merger hypothesis is correct, whether the system is being viewed before or after core passage is dependent on the viability of the lower velocity component in the KMM fits. P96 note that the difference in the velocity dispersions of the two components (for ease of reference, hereafter called the primary and the subcluster) is a good diagnostic of the timing of the merger (see their Table 9). Prior to core passage, the velocity dispersion of the primary is larger than that of the subcluster simply because of its greater mass. As the subcluster merges with the primary, it is dispersed and thereby obtains the larger dispersion. In the two-component KMM fit, the subcluster has a slightly lower velocity dispersion and would then indicate that the system is being viewed shortly before core passage (see Table 6). Removing the lower velocity galaxies from the primary when going to a three-component fit reduces the dispersion of the primary below that of the subcluster, suggesting that the system is viewed shortly after core passage. In either case the high relative velocity of subcluster to the primary, 1940 km s$^{-1}$ in the two-component fit and 1702 km s$^{-1}$ in the three-component fit, is consistent with viewing a merger near the time of core passage (see, e.g., eq. [15] and associated discussion in Sarazin 2002).

A simple sanity check on the merger hypothesis is to ask whether the presumed merging parties are bound. Treating the primary and subcluster as point masses, the simple Newtonian condition for a bound system is

$$V_r^2 R_p \leq 2GM \sin^2 \alpha \cos \alpha,$$

where $V_r$ is the line-of-sight velocity difference between the two masses, $R_p$ is their projected separation, $M$ is the total mass, and $\alpha$ is the projection angle defined from the plane of the sky. The KMM analysis provides a reference from which to evaluate this condition, in particular by providing estimates for $V_r$, $R_p$, and $M$ (under the assumption that both the primary and the subcluster represent virialized systems). In the two-component fit, $V_r = 1940$ km s$^{-1}$, $R_p = 700$ kpc, and $M = 3.4 \times 10^{15} M_\odot$ (the virial masses for the primary and subcluster are $2.1 \times 10^{15}$ and $1.3 \times 10^{15} M_\odot$, respectively). Thus, the system is bound for nearly all projection angles ($6^\circ \leq \alpha \leq 84^\circ$). Only if the total mass of the system is very low ($\lesssim 8 \times 10^{14} M_\odot$) would the system be unbound. Similarly, using the two largest components in the three-component fit, the system would be bound for $5^\circ \leq \alpha \leq 85^\circ$ and unbound if $M \lesssim 5 \times 10^{14} M_\odot$. Note that in the latter case, the virial assumption is surely suspect as the subcluster has the larger velocity dispersion and hence implied mass ($0.9 \times 10^{15} M_\odot$ for the primary and $1.4 \times 10^{15} M_\odot$ for the subcluster).

This merger hypothesis is potentially further supported by the X-ray morphology, although as with the case of a simple superposition there are difficulties. The X-ray emission of the main body of A2125 is elongated in a direction perpendicular to the low surface brightness X-ray emission. This elongation is consistent with “an initial coalescence of subunits of comparable masses” (Wang et al. 1997), whereas at later stages the elongation would tend to be along the supercluster filament (see also the simulations of Roettiger et al. 1997). However, it is clear that the X-ray emission from the main body of A2125 represents only a small portion of the entire system (refer to Fig. 4). While a merger of some sort is indicated by the X-ray data, the scale of this merger is debatable.

In any case, we are observing A2125 under special circumstances that may largely explain some of the peculiarities of the cluster. At richness class 4, it is among the very richest clusters of galaxies known (e.g., Morrison et al. 2003). Similarly, its large velocity dispersion suggests that it is a massive cluster containing many galaxies. However, these factors are inconsistent with the low X-ray luminosity and temperature of the cluster ($L_X = 7.9 \times 10^{45}$ ergs s$^{-1}$ and $T = 3.2$ keV; Wang et al. 2004). For example, using the $\sigma$-$T$ relationship of Lubin & Bahcall (1993), the velocity dispersion of A2125 would predict a temperature of 7.5 keV. Such a discrepancy can be explained if the system is composed of multiple complexes seen in projection, whether these components are merging or not. A more appropriate application of the $\sigma$-$T$ relationship would then be for an individual cluster in the system. Working backward, the X-ray temperature predicts a velocity dispersion of about 670 km s$^{-1}$, a figure in line with the velocity dispersions of the larger substructures (i.e., components with the most members) identified in the KMM analysis (refer to Table 6).

### 4.2. Emission-Line versus Non–Emission-Line Galaxies

As prior studies (e.g., Owen et al. 1999; Morrison et al. 2003) have noted an excess in the fraction of active galaxies in A2125 relative to other clusters of comparable richness, we performed a simple investigation of activity as defined by the presence of emission lines. For this purpose, the noted presence of any emission line in a galaxy’s spectrum regardless of the strength of that line was sufficient for inclusion of that galaxy in the emission-line sample. Using this definition, 75 of 224 cluster galaxies (33.5%) were emission-line objects. Unfortunately, we lack comparable data sets for other intermediate-redshift clusters to test whether this fraction is unusually high. For comparison, 96 of the 151 noncluster galaxies in the field of A2125 (63.6%) were emission-line objects.

When measured over the entire cluster, the dynamics of the emission-line galaxies does not differ significantly from that of the non–emission-line galaxies. The systemic velocity and dispersion for the emission-line galaxies were $73,798 \pm 133$
and $1148^{+107}_{-84}$ km s$^{-1}$, respectively, while those for the non-emission-line galaxies were $73, 950 \pm 90$ and $1092^{+70}_{-58}$ km s$^{-1}$. Similarly, there is no significant evidence that the emission-line galaxies are drawn from a different population than the cluster galaxies as a whole, as quantified by KS and Wilcoxon tests. The positional data suggest that the emission-line galaxies are at lower declinations, although this is significant only at $1.85 \sigma$. We also checked whether the emission-line galaxies were preferentially associated with any substructures identified via the KMM analysis. A $\chi^2$ test indicated that there was no statistical difference in the fraction of galaxies with emission lines among the various groups. Thus, the emission-line galaxies are fairly well mixed throughout the cluster.

5. CONCLUSIONS

We have reported on a program that has obtained 371 galaxy velocities in the direction of the $z = 0.2465$ rich cluster A2125. These new velocities include 222 cluster galaxies (including 25 in common with those reported in Owen et al. 1999), which increases the total number of confirmed cluster members to 224, making this among the better studied intermediate-redshift Butcher-Oemler clusters. The galaxy velocities were subjected to a large number of statistical tests that identified significant substructure. Through comparison with numerical simulations, these tests indicated that A2125 is consistent with a merger of comparable-mass clusters viewed along an axis within $\sim 30^\circ$ of the merger axis. This merger is viewed within a few hundred million years of the time at which the cores of the respective components have crossed. A favorable alignment of multiple structures, be they involved in a merger or simply seen in projection, is helpful in understanding the general properties of A2125. The combination of these structures produces an unusually high richness and velocity dispersion, reconciling the apparent discrepancy of the richness of the cluster with its low X-ray temperature and luminosity.

We are deeply saddened by the passing of Michael Ledlow. His enthusiasm for astronomy was surpassed only by the kindness of his heart, and he will be sorely missed.

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