*Carnegie Observatories Astrophysics Series, Vol. 3:
Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution, 2004
ed. J. S. Mulchaey, A. Dressler, and A. Oemler (Pasadena; Carnegie Observatories:
http://www.ociw.edu/ociw/symposia/series/symposium3/proceedings.html)*

The Deep, Wide-field Hα Survey of Nearby Clusters of Galaxies

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Abstract

We present preliminary results from our Hα imaging survey of nearby Abell clusters, which was conducted using the Mosaic CCD Imager on the 0.92m telescope at KPNO. We find that grism-based surveys that were used to measure the star formation rate in the local Universe might have missed significant amount of star formation. We have also discovered a remarkable group of actively star-forming dwarf galaxies and HII galaxies in A1367. Based on optical and radio observations, we favor a tidal origin for the evolution of this group.

1.1 The Hα Survey

We have been conducting a deep, wide-field Hα imaging survey of nearby clusters of galaxies. The main goals of this survey are: (1) to construct a complete inventory of star forming galaxies in a well-defined volume limited sample; (2) to characterize the demographics and environment of the local star forming population; and (3) to quantify the completeness of other methods for measuring the local SFR density. With the Mosaic CCD Imager on the 0.92m telescope at KPNO, we are able to cover an 1° field in a single observation. The total integration time of 90 minutes allows us to reach limiting fluxes corresponding to star formation rates (SFRs) of about 0.1 $M_\odot$/yr for extended galaxies and $\sim$0.01 $M_\odot$/yr for compact emission-line galaxies.

Each frame was visually searched for galaxies with emission-line excess in the Hα filter. We had considered using automated software, such as S-Extractor, but the human eye turns out to be extremely sensitive and efficient in picking out emission-line regions, or differences between two frames. Once a very long list of Hα-emitting galaxies, that included all possible candidates, was made, smaller postage stamp images for all the galaxies were made, which were then used to subtract the continuum from the narrow-band images, and to estimate the equivalent widths and fluxes. In order to achieve the goals above, we surveyed a total of 25 square-degree fields in eight Abell clusters in the radial velocity range 3000-8000 km s^{-1}: A262, A347, A400, A426, A569, A779, A1367 and A1656. These clusters were chosen as they had been targeted by the prism survey of Moss, Whittle and collaborators (Moss, Whittle & Pesce 1998). We could then compare our results with theirs, to examine if and how the grism survey is biased in measuring the SFRs. For most clusters, more than one narrow-band filter, from the KPNO/Mosaic set, was used in order to cover the velocity dispersion of clusters. The effective bandwidth of each filter is approximately 80 Å. On

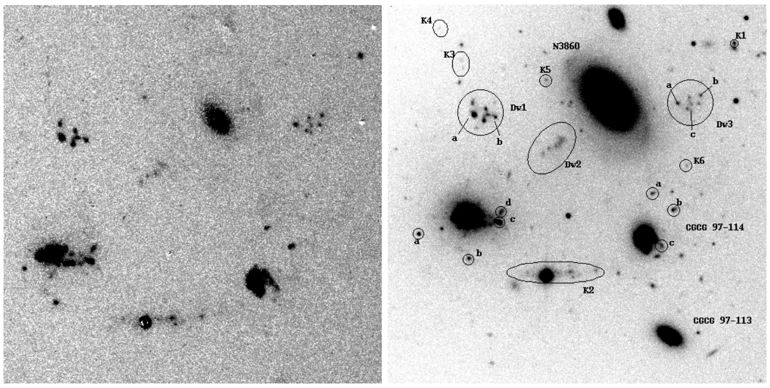

Fig. 1.1. CGCG97-114/125 group, in Hα (*left*) and continuum.

26 Mosaic fields, we found 625 galaxies with emission of equivalent width larger than 4 Å which corresponds to approximately a 2σ detection.

1.2 Comparison with Other Hα Surveys

One of the main goals of this survey is to study how complete the grism-based surveys are in searching for Hα emission-line galaxies. We compared our sample with two existing surveys: the first by Moss, Whittle and collaborators (e.g. Moss, Whittle & Pesce 1998) which used an objective prism technique, and the second by the CCD-based KISS Survey (Salzer et al 2000). Even though the flux measurements are not finalized in our sample yet, we can easily estimate which survey has detected more or less galaxies with Hα emission. We find that the Moss & Whittle sample misses almost 50% of the total Hα flux in each cluster. On the other hand, the CCD-based KISS Survey is 80% complete. Although this excludes galaxies without published velocities, preliminary results of our follow-up redshift survey at Lick indicate that more than 90% of the observed galaxies are indeed cluster members, and not background objects.

1.3 Discovery of A Group of Star-forming Dwarf Galaxies in Abell 1367

One region stood out in the central field of A1367: we serendipitouly found a group of actively star-forming dwarf galaxies, consisting of $\sim$30 individual HII regions, (Sakai et al 2002, Figure 1). The group spans approximately 4'-5' on the sky, corresponding to a linear diameter of 110-130 kpc, if we adopt a distance to A1367 of 93 Mpc (Sakai et al 2000).

Most of the galaxies found in this CGCG 97-114/125 Group are not cataloged (e.g. in the NASA Extragalactic Database). The most prominent galaxy in this field, NGC 3860, however, is likely a foreground object. Its radial velocity is offset from most of the objects by 2600 km s^{-1} (cz=5600 km s^{-1} for NGC 3860 vs. 8200-8300 km s^{-1} for the group; de Vaucouleurs et al. 1991; Giovanelli et al. 1997; Haynes et al. 1997).

The objects in this group are: (1) two previously cataloged Zwicky galaxies, CGCG 97-114 and 97-125 with multiple HII regions in their disks, (2) previously unidentified dwarf galaxies, (Dw1, Dw2 and Dw3 in Fig. 1), and (3) isolated intergalactic HII knots, with no detectable underlying stellar components (Knot 1 (K1) and K2).

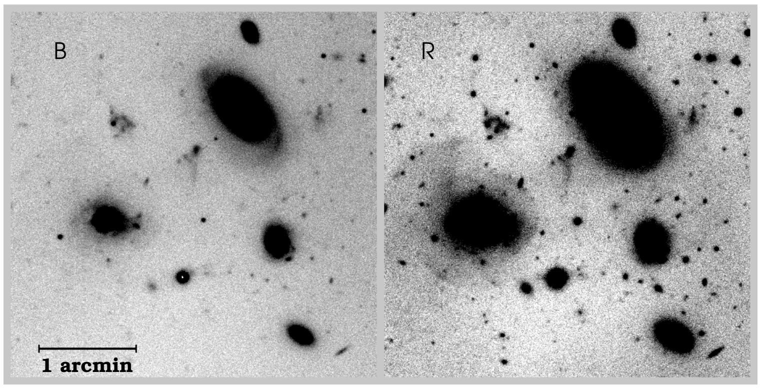

Fig. 1.2. Broadband images of the CGCG97-114/125 group.

The Zwicky galaxies both show peculiar morphologies. The broadband images of CGCG 97-125 show a faint, diffuse shell-like feature, characteristic of dynamically disturbed galaxies or merger remnants (e.g., Malin & Carter 1983; Schweizer & Seitzer 1988). The images also reveal a faint bridgelike tail extending to the west of CGCG 97-125, along with faint arms of HII knots (K2 in Figure 1) between the two galaxies. The Hα+ [NII] equivalent widths of CGCG 97-114 and 125 are 44 and 29 Å respectively, typical for actively star-forming late-type spiral and irregular galaxies (Kennicutt & Kent 1983). Some of the HII regions in the vicinity of Zwicky galaxies appear isolated, not physically associated with a galaxy.

Dwarf galaxies: The magnitudes of the dwarf galaxies are $B = 18.35 \pm 0.05, 18.2 \pm 0.10$, and 19.09 ± 0.15 mag, respectively, for Dw1, Dw2 and Dw3. At the distance modulus of 34.84 mag (Sakai et al. 2000), these galaxies have luminosities comparable to the SMC, but the stellar structures are less concentrated and more chaotic. All three dwarf galaxies are very blue, with $B-R = 0.05 \pm 0.07$, 0.53 ± 0.14 and 0.20 ± 0.21 mag for Dw1, Dw2 and Dw3 respectively. Dw1 is the most actively star-forming object with an Hα+[NII] equivalent width of 101 $\pm$ 4 Å, which requires a current SFR several times higher than the time-averaged past SFR in the galaxy, and is comparable to some of the most extreme starburst galaxies.

Isolated HII Galaxies and HII Regions: Over a dozen of the emission regions in the group do not show any obvious association with any of the galaxies, either the luminous CGCG galaxies or the fainter dwarfs described above. Some knots appear to be associated with larger-scale features, such as K2, the bridge-like feature connecting CGCG 97-125 and 97-114. On the other hand, for other knots, an unambiguous association with a nearby galaxy is impossible due to the disturbed nature of galaxies in this group.

Deep broadband images do reveal stellar components in almost all of these knots. Their typical magnitudes range from $B \sim R \sim 21-23$, corresponding to absolute magnitudes of -11 to -13. These are comparable to those of luminous stellar associations in normal spiral and irregular galaxies, or the faintest dwarf irregular galaxies. The isolated HII region knots show extremely strong emission, with EW's in the range 200-400 Å. They resemble ordinary HII regions in nearby galaxies in EW, luminosity, and continuum color.

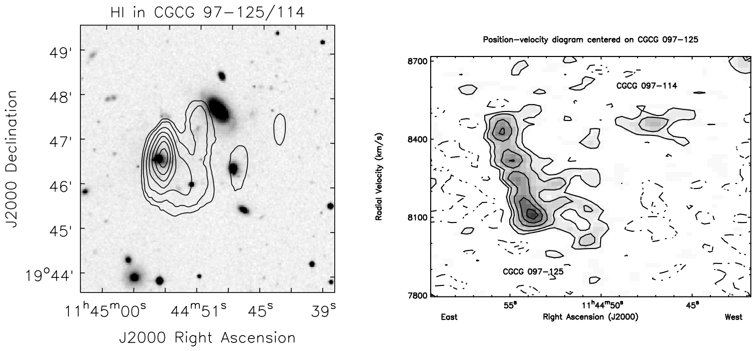

Fig. 1.3. (*left:*) HI column density distribution in the CGCG 97-114/125 group overlaid on the XDSS blue image. (*right:*) HI position-velocity diagram centered on CGCG 97-125.

1.3.1 What is the Origin of this Group?

There are three possible explanations for this group of actively star-forming galaxies: (1) A normal compact group of field galaxies observed in projection behind A1367; (2) The unusual star formation properties of the group are due to a strong interaction with the intergalactic medium in A1367, caused by shocking of the interstellar medium as this group moves through the intergalactic medium (IGM) with an encounter velocity of 1600 km s^{-1}; and (3) The unusual star formation properties are caused by current and/or past tidal encounters between two or more of the galaxies in the group, independent of the cluster environment outside of the group.

The possibility that the CGCG 97-114/125 group is merely a normal group of galaxies which happen to comprise more than a few actively star-forming objects is very unlikely. If this were the case, one would expect to see quiescent galaxies as well. Induced star formation from IGM interactions is not as easily ruled out, especially because evidence for such processes is found elsewhere in A1367 (Gavazzi et al. 1995). However, none of the galaxies in this group show evidence of bow shock structure in the Hα or broadband images or asymmetric HI distributions (see Figure 3). In addition, we would expect a 1600 km s^{-1} encounter between the galaxy ISMs and the A1367 IGM to produce soft X-ray emission, but Chandra maps of this region do not show any extended emission (Sun et al. 2001, Sun & Murray 2002).

Instead, Hα and broadband imaging, and also optical spectroscopy and HI imaging favor the third scenario: tidal interactions between galaxies. First, the very disturbed appearance of the Zwicky galaxies, especially a shell-like feature of CGCG 97-125, suggest that these galaxies have undergone an interaction. In addition, there is evidence for tidal structures connecting many of the emission regions in the HI maps. The HI column density image of the group (Figure 3) shows that CGCG 97-125 and 114 are clearly detected, with masses $3.9x10^9 M_\odot$ and $3.0x10^8 M_\odot$ respectively. The relatively high SFR in CGCG 97-125 (EW=29) is consistent with its large HI content, but the even higher SFR in CGCG 97-114 is surprising in terms of its low HI mass.

The HI distribution is very extended (Figure 3), especially around CGCG 97-125, connecting this galaxy to Dw1, Dw2 and the "bridge" between CGCG 97-125 and 114. The

HI is also extended in the velocity dimension as shown in the right panel of Figure 3. The velocity of CGCG 97-125 ranges from 8090 up to 8490 km s^{-1}. If this reflects the rotation of the disk, it translates to a projected rotation speed of 200 km s^{-1} or $\sim$340 km s^{-1} when corrected for i = 36^{o} (Haynes et al 1999). This is exceptionally high for an $M_B = -19.1$ galaxy, which usually has a rotation speed of $\sim$200 km s^{-1} (Broelis 1992; Verheijen 1997).

The third piece of evidence supporting the tidal interaction scenario is the abundances of the galaxies and HII regions in this group, which are much higher than expected for the size of these dwarf galaxies. The oxygen abundances of HII regions and knots are $12+\log(O/H) = 8.3-8.9$ or $0.25-1.0$(O/H)$_{\odot}$. If Dw1 and Dw3 were isolated galaxies, then we would expect them to lie on the metallicity-luminosity relation (Skillman et al 1989). For $M_B = -15.8$ to -16.5, a typical oxygen abundance is $12+\log(O/H) = 8.0\pm0.3$. Instead, we find that Dw1 and Dw3 are more metal-rich by a factor of 2 or more. But this difference is marginally significant, given the accuracy of the abundance measurements, the dispersion in the metallicity-luminosity relation, and a possible offset between the R_{23} and [NII]/[OII] index calibrations of Kewley & Dopita (2002).

The abundances of isolated knots, K2, however, strongly favor the tidal interaction scenario. If these knots were isolated objects, then their expected abundances would be $1/40-1/20$ solar. However, the observed abundances are comparable to those of CGCG 97-125, which rule out any evolutionary scenario in which the intergalactic knots (e.g. K2) are isolated, normal dwarf galaxies evolving as closed systems. Instead, the high abundances favor a picture in which the K2 knots formed from enriched material stripped from one of the larger galaxies, perhaps in a recent tidal interaction.

No other comparable subgroups or subclusers of star-forming regions have been found elsewhere in our Abell cluster survey, which covers 25 deg^2 and a search volume of approximately 300 Mpc^3 in eight clusters.

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