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THE CURRENT STAR FORMATION RATE OF K+A GALAXIES

Danielle M. Nielsen[1,2], Susan E. Ridgway[2,3], Roberto De Propris[2], and Tomotsugu Goto[4]
[1] Department of Astronomy, University of Wisconsin-Madison, 475 North Charter Street, Madison, WI 53706, USA; nielsen@astro.wisc.edu
[2] Cerro Tololo Inter-American Observatory Casilla 603, La Serena, Chile
[3] National Optical Astronomy Observatory, 950 N. Cherry Avenue, Tucson, AZ 85719, USA
[4] Dark Cosmology Center, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen Ø, Denmark
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ABSTRACT

We derive the stacked 1.4 GHz flux from the FIRST survey for 811 K+A galaxies selected from the Sloan Digital Sky Survey Data Release 7. For these objects we find a mean flux density of $56 \pm 9\ \mu$Jy. A similar stack of radio-quiet white dwarfs yields an upper limit of 43 μJy at a 5σ significance to the flux in blank regions of the sky. This implies an average star formation rate of $1.6 \pm 0.3\ M_\odot$ yr^{-1} for K+A galaxies. However, the majority of the signal comes from ~4% of K+A fields that have aperture fluxes above the 5σ noise level of the FIRST survey. A stack of the remaining galaxies shows little residual flux consistent with an upper limit on star formation of 1.3 $M_\odot$ yr^{-1}. Even for a subset of 456 "young" (spectral ages <250 Myr) K+A galaxies, we find that the stacked 1.4 GHz flux is consistent with no current star formation. Our data suggest that the original starburst has been terminated in the majority of K+A galaxies, but that this may represent part of a duty cycle where a fraction of these galaxies may be active at a given moment with dusty starbursts and active galactic nuclei being present.

Key words: galaxies: evolution – galaxies: starburst – radio continuum: galaxies

Online-only material: color figures

1. INTRODUCTION

K+A galaxies, also known as post-starburst galaxies (PSGs), show spectra of a strong Balmer absorption series superposed over a K-giant-dominated spectrum typical of early-type galaxies, implying the recent termination (<1 Gyr) of a significant episode of star formation in an otherwise quiescent stellar population (Dressler & Gunn 1983; Couch & Sharples 1987). These objects may be the best examples of galaxies transitioning from the "blue cloud" (of star-forming objects) to the "red sequence," and have often been identified as possible progenitors of the lenticular population in clusters (Yang et al. 2004, 2008), rejuvenated early-type galaxies (e.g., Panuzzo et al. 2007), or the descendants of the blue galaxies observed in intermediate-redshift clusters (Zabludoff et al. 1996; Poggianti et al. 1999).

The mechanism by which star formation is initiated and/or quenched in these galaxies is still unclear. The majority of local K+A galaxies lie in the general field rather than clusters (Blake et al. 2004; Goto 2007; Vergani et al. 2010) and the processes that trigger and halt star formation may differ in these environments. At the same time, in the intermediate-redshift clusters where K+A galaxies were originally discovered, a significant fraction of current star formation is obscured by dust (Duc et al. 2002; Saintonge et al. 2008; Dressler et al. 2009; Haines et al. 2009). Dusty starbursts tend to have strong Balmer absorption but only weak O II emission as the young stars and H II regions that produce the emission lines tend to lie in regions of high extinction while the longer lived A-stars can migrate out of their native molecular cloud: this would be a viable model to explain the K+A spectral class (Poggianti & Wu 2000). Therefore, it is still unclear whether K+A galaxies are truly "red and dead," although the 24 μm observations of Dressler et al. (2009) in A851 imply that star formation has largely ceased in these objects.

Obscured star formation may also be detected via radio emission at 20 cm (1.4 GHz), which is produced by synchrotron radiation from high-energy cosmic rays originating in supernova shells and yields a measure of the massive star formation rate (SFR; Condon 1992; Kennicutt 1998). Although Smail et al. (1999) found evidence of recent star formation in 5 K+A galaxies, other studies find little evidence of ongoing star formation within small samples (Miller & Owen 2001; Goto 2004). However, Buyle et al. (2006) found that most K+A have substantial gas reservoirs, similar to those of spirals of the same luminosity, and suggest that K+A galaxies may be observed during a hiatus in an episodic star formation history or that current star formation may be obscured.

In this Letter we use a stack of radio images to further test the current SFR and/or active galactic nucleus (AGN) activity in spectroscopically selected K+A galaxies. A description of the data and the analysis is provided in the next section, while we interpret and discuss our results in Section 3. We adopt the latest *Wilkinson Microwave Anisotropy Probe* cosmological parameters with $\Omega_{\rm M} = 0.27$, $\Omega_\Lambda = 0.73$, and $H_0 = 71$ km s^{-1} Mpc^{-1}.

2. FIRST RADIO STACKING OF THE SDSS DR7 K+A SAMPLE

We select a sample of 811 K+A galaxies from Data Release 7 (DR7) of the Sloan Digital Sky Survey (SDSS; York et al. 2000; Abazajian et al. 2009) using an updated catalog of Goto (2007). Only objects classified as galaxies with a spectroscopic signal-to-noise ratio >10 per pixel are considered. The selection criteria of K+A galaxies are equivalent widths of H$\alpha > -3.0$ Å, H$\delta > 5.0$ Å, and [O II] > -2.5 Å, where emission lines are negative. Galaxies of redshift $0.35 < z < 0.37$ are excluded from the sample due to the 5577 Å sky feature. The selected sample of K+A galaxies has redshifts ranging $0.02 < z < 0.4$.

We then use data from the FIRST survey (Becker et al. 1995) to derive a mean radio image of K+A galaxies. Typical detection limits for a single FIRST image are ~1 mJy, which, for the mean redshift from our SDSS DR7 sample of K+A galaxies, would only allow us to detect SFRs in excess of 30 $M_\odot$ yr^{-1}.

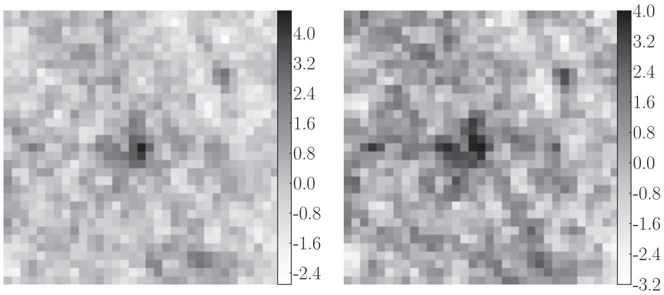

Figure 1. Left: the median stack of FIRST images of 811 K+A galaxies selected from the SDSS. The image is 1′ square with gray-scale units in μJy. Right: the median stack of 427 K+A galaxies with less than 250 Myr since the end of the starburst. The image is 1′ square with gray-scale units in μJy.

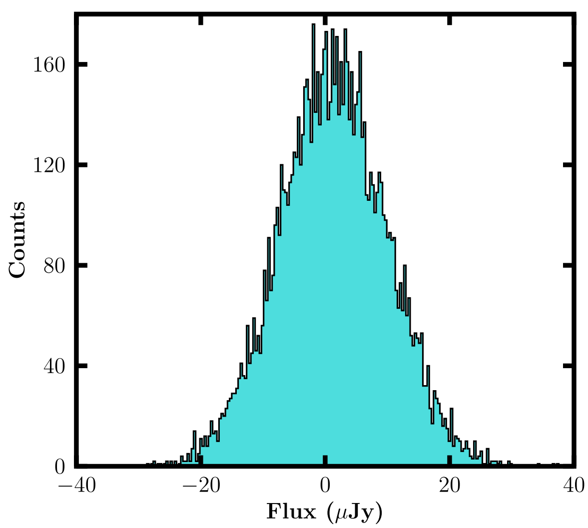

Figure 2. Histogram of fluxes from Monte Carlo stacks of white dwarfs in the SDSS. Each stack is equivalent to the stack of K+A galaxies used in the analysis and contains 811 white dwarfs images. We find a 5σ noise level of 43 μJy.

(A color version of this figure is available in the online journal.)

For each of the 811 K+A galaxies covered by the survey we cut out a 1′ square from the FIRST database. We use the median stacking method of White et al. (2007) to create the resulting image of 811 K+A galaxies shown in the left panel of Figure 1. We then measure the flux from the combined image in an aperture equivalent to three FIRST beams from which we derive an average K+A flux of $56 \pm 9\ \mu$Jy.

To assess the significance of this result, we need to estimate the level of noise in the image. As FIRST is a survey, the image cutouts may not be fully cleaned of artifacts, such as side lobes from distant radio sources. To do this, we use a Monte Carlo simulation with a sample of known radio-quiet objects, 8495 white dwarfs from the SDSS (Eisenstein et al. 2006). We create 10,000 stacks of 811 randomly selected white dwarfs (equivalent to the stack of K+A galaxies) and measure the flux in the same fashion to derive the mean flux from a supposedly radio-quiet sample.

This procedure allows us to estimate the level of noise present in the stacked image and therefore to determine the significance of our detection for K+A galaxies. A histogram of the fluxes from our Monte Carlo simulation is shown in Figure 2. Since we know that these sources are radio quiet, we can estimate a 5σ significance flux for sources to be considered real. We find this flux to be 43 μJy. Our K+A stack is found to have a significant detection above the 5σ noise level.

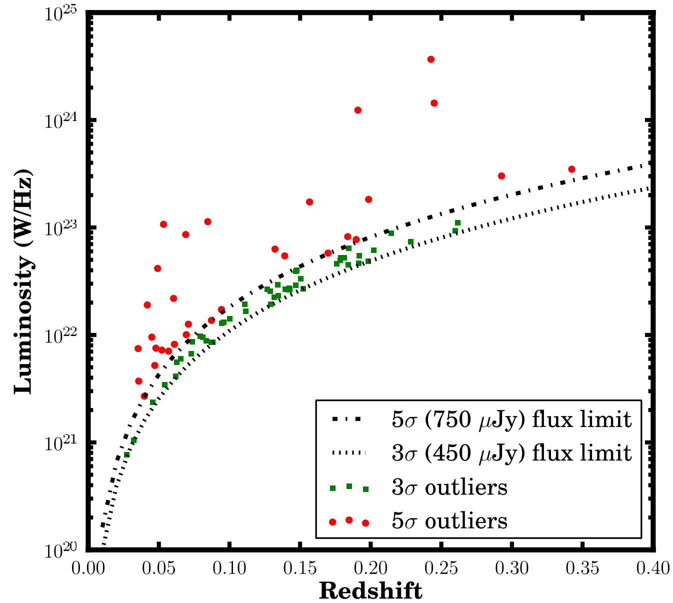

Figure 3. We have plotted K+A galaxies from our sample with aperture fluxes in excess of 3σ and 5σ as green squares and red circles, respectively. The dotted and dot-dashed lines indicate the 3σ and 5σ FIRST survey limits, respectively, as a function of redshift.

(A color version of this figure is available in the online journal.)

We can now compute the absolute luminosity at 1.4 GHz using our chosen cosmology and the average redshift of the K+A galaxies ($z = 0.14$):

$$L_{1.4\,\mathrm{GHz}} = 4\pi D_L^2 S_{1.4\,\mathrm{GHz}} (1+z)^{\alpha}/(1+z), \qquad (1)$$

where D_L is the luminosity distance, $S_{1.4\,\mathrm{GHz}}$ is the flux density, $(1+z)^{\alpha}$ is the color correction, and $1/(1+z)$ is the bandwidth correction (Morrison et al. 2003). We assume that the radio emission is dominated by synchrotron radiation such that $S \propto \nu^{-0.8}$ (Condon 1992). This yields our measurement of radio power, which we can convert to an SFR using

$$\mathrm{SFR}\ (M_\odot\ \mathrm{yr}^{-1}) = 5.9 \times 10^{-22} L_{1.4\,\mathrm{GHz}}\ (\mathrm{W\ Hz}^{-1}), \qquad (2)$$

from Yun et al. (2001), which assumes a Salpeter initial mass function (IMF) between 0.1 and 100 solar masses. This yields an SFR of $1.6 \pm 0.3\ M_\odot\ \mathrm{yr}^{-1}$ for our average K+A galaxy at $\langle z \rangle = 0.14$.

However, 79 of our sources are measured to have 1.4 GHz fluxes above the 3σ noise level of the FIRST survey. The FIRST beam has an rms of 0.15 mJy and we find that 79 galaxies ($\sim$10%) have aperture fluxes in excess of 3σ (450 μJy) within an aperture of 3 beam sizes, 31 of which have fluxes in excess of 5σ (750 μJy).

In Figure 3 we show the redshift–luminosity distribution of the targets with aperture fluxes above the 3σ and 5σ limits. Visual inspection of these individual outlier frames has shown that for the 31 galaxies above the 5σ limit, about 80% look like clear individual detections (i.e., centrally concentrated, likely to be associated with our optical target, not in a frame that is significantly noisy), while for the 48 that are above the 3σ limit but less than the 5σ limit, only about 10% of these are clear detections. Overall only about 4% of our sample of 811 galaxies show evidence of significant ongoing radio activity, either from star formation or AGN activity.

Removing all sources with measured fluxes in excess of 5σ, we create a subsample of 780 galaxies. Stacking this subsample

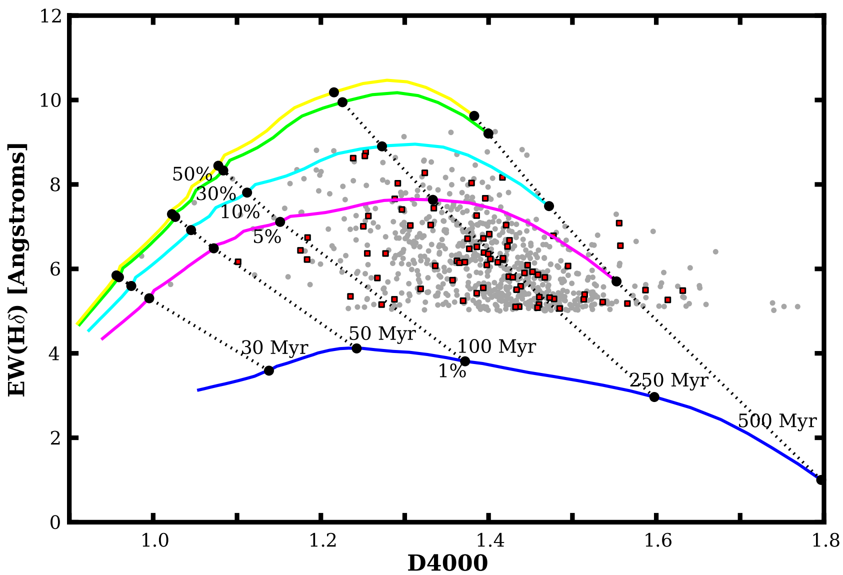

Figure 4. Plot of Hδ and D4000 for K+A galaxies from SDSS spectra and models. The gray circles and red squares are the measured values for K+A galaxies. The red squares indicate galaxies with significant 1.4 GHz detections. The solid lines are the models of an old 10 Gyr exponentially decaying stellar population with a burst of 1% (blue), 5% (purple), 10% (cyan), 30% (green), and 50% (yellow) mass relative to the older stellar population. The dotted lines indicate the values of the spectral indices when observed 30, 50, 100, 250, and 500 Myr after the burst.

(A color version of this figure is available in the online journal.)

yields a mean flux of 36 μJy, which is well below the 5σ detection limit of 47 μJy found from a Monte Carlo simulation creating stacks of 780 white dwarfs. We can place an upper limit on the SFR of 1.3 $M_\odot$ yr^{-1} for this subsample with $\langle z \rangle = 0.14$.

When star formation ceases in a galaxy, we expect it to decrease exponentially to low levels, rather than an abrupt truncation, unless some "catastrophic" event has removed all the available fuel or ionized the gas and prevented further star formation. Evidence for a rapid shutdown of star formation in these galaxies has been presented by Brown et al. (2009). We therefore carry out the same analysis on a subsample of "young" K+A galaxies and attempt to detect residual star formation in these objects.

In Figure 4, we plot Hδ and D4000 from SDSS spectra and overplot models calculated with GALAXEV (Bruzual & Charlot 2003). We plot the galaxies with significant 1.4 GHz detections as red squares, the rest as gray dots. We adopt a Salpeter IMF and solar metallicity as initial conditions. The model galaxies evolved over 10 Gyr with an exponentially decreasing SFR ($\tau = 1$ Gyr). At 10 Gyr, we added an instantaneous starburst (delta function) of mass 1%, 5%, 10%, 30%, and 50% (relative to the old stellar population) after which the SFR returns to zero. The dotted lines demarcate the values of the spectral indices observed 30, 50, 100, 250, and 500 Myr after the burst. These are the same models used by Yagi et al. (2006) and Goto et al. (2008).

We then select the 456 K+A galaxies with burst ages less than 250 Myr and an average redshift of $\langle z \rangle = 0.13$ and stack these galaxies in the same fashion as the complete sample. The stacked image is shown in the right panel of Figure 1 from which we measure a mean flux of 61 μJy. The Monte Carlo simulation with white dwarfs gives a 5σ detection limit of 59 μJy. Our younger sample of K+A galaxies is found to be at the 5σ detection limit, giving an SFR of 1.5 ± 0.3 $M_\odot$ yr^{-1}. This is consistent with a rapid decline of star formation in these galaxies as shown by Brown et al. (2009).

3. DISCUSSION

We have found an average SFR of only 1.6 ± 0.3 $M_\odot$ yr^{-1} from stacking radio observations of 811 general field K+A galaxies in the local universe.

However, much of this signal appears to originate from ~4% of active galaxies. Based on the definition of Sadler et al. (2002), which requires radio power above 10^{23} W Hz^{-1} and the absence of emission lines, this sample is approximately equally split between star-forming galaxies and AGNs (with the latter more prominent at higher redshifts because of selection effects).

For the remainder of the sample, we find an upper limit on the SFR of 1.4 $M_\odot$ yr^{-1}. Even a subsample of spectroscopically young galaxies does not show a significant detection of residual star formation.

Our results are in good agreement with previous work. Goto (2004) did not detect evidence of star formation from Very Large Array (VLA) observations in 36 galaxies drawn from the SDSS DR1 (Goto et al. 2003) but he was able to set an upper limit of <15 $M_\odot$ yr^{-1} for 15 of the nearest K+A galaxies. Miller & Owen (2001) found that only two out of 15 K+A galaxies in his sample show signs of obscured star formation. Nevertheless, Melnick & de Propris (2012) find that most K+A galaxies in this sample exhibit significant excess above the predicted stellar component at $\lambda > 5$ μm from *WISE* data, suggesting that dust heated by some unknown source is present in these objects.

Buyle et al. (2006) pointed out that K+A galaxies contain significant amounts of gas and therefore the current quiescent star formation may only be temporary, while Poggianti & Wu (2000) proposed a model where star formation continues in K+A galaxies but is hidden by dust. However, Dressler et al. (2009) detected no 24 μm emission for K+A galaxies in A851.

Another possible contribution to the radio flux is that K+A galaxies may host an AGN. Most K+A galaxies have significant bulges (Yang et al. 2008) and therefore should contain a supermassive central black hole (e.g., Ferrarese & Merritt 2000). In the general field, K+A galaxies are often involved in mergers and interactions (Blake et al. 2004; Goto 2005; Yang et al. 2008) and show inverted color gradients indicative of central star formation (Yang et al. 2008), which is expected if mergers drive gas to the center (Hernquist 1989).

Liu et al. (2007) find evidence of a weak AGN in a nearby K+A galaxy. However, Shin et al. (2011) find only a few AGNs in a subset of our sample and they argue that these active nuclei are not related to the quenching of the previous starburst. Brown et al. (2009) argue that AGN feedback is only important among the more massive K+A galaxies. Vergani et al. (2010) find no evidence for AGN in their sample of COSMOS K+A galaxies using deep VLA and *XMM* imaging of the COSMOS field and only a small number of star-forming objects, in agreement with our results. On the other hand, Georgakakis et al. (2008) argued for a weak correlation between AGN and K+A galaxies in the Extended Groth Strip field.

Snyder et al. (2011) present a model where K+A galaxies originate from gas-rich mergers and the duration of the Balmer-line strong phase is shorter than the commonly assumed $\sim$1 Gyr by about a factor of 3. In this framework the $\sim$4% of "active" galaxies that we find may be the tail end of the distribution, while other objects are already heading towards the red sequence. In this case, this might yield a constraint on the activity timescale, assuming a 0.3 Gyr duration for the K+A phenomenon. If the 4% of active galaxies represent the last gasp of activity before the AGN returns to a dormant state, the period of visible QSO activity may be estimated to be about 20 Myr, which is broadly consistent with current estimates (e.g., see review by Martini 2004).

Another plausible explanation is that we are actually observing galaxies undergoing a series of starbursts and feedback episodes, as in the cycle postulated by Hopkins et al. (2008) to account for the tightness of the red sequence within a hierarchical formation framework. In which case we would be observing galaxies in the "on" and "off" phases of such a cycle.

Shioya et al. (2002) present a model where truncated spirals evolve through the e(a) (galaxy with strong Hδ and modest O II emission), a+k, and finally k+a phase before settling on the red sequence. If we are observing galaxies at random along their spectrophotometric transformation, and given the $\sim$0.3 Gyr duration of the most visible k+a phase, the timescale for evolution of these galaxies on to the red sequence is long, $\sim$7 Gyr, which is consistent with the above simulations. Only low-mass objects can then truly evolve on to the red sequence in reasonable times.

A series of questions remain unanswered. Do K+A galaxies host ongoing dusty starbursts? This appears unlikely in the light of our results, but the detection of powerful far-infrared excesses by Melnick & de Propris (2012) points to the existence of extra sources of flux that are heavily obscured. What is the role of an AGN (if any) in modulating the rapid onset and decline of star formation? Do these objects contain cold gas and possibly re-initiate star formation? Future papers by our group will attempt to address some of these issues.

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