

Star Formation Histories and Stellar Dynamics in the Central Galaxies of RX J0820.9+0752, A1835, and PKS 0745-191

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ABSTRACT

We present Keck Cosmic Web Imager observations of stellar populations in three galaxies at the centers of cooling flow clusters. All three host rich molecular gas reservoirs and show prominent Balmer absorption from 30–100 Myr-old stars consistent with long lasting star formation. Two systems, A1835 and PKS 0745-191, have extended young stellar populations in their centers with recent star formation rates of $100 \text{ M}_{\odot} \text{ yr}^{-1}$ and $8 \text{ M}_{\odot} \text{ yr}^{-1}$, respectively. In A1835 we uncover a massive blueshifted clump of young stars moving at high speed with respect to the gas and central galaxy. We suggest this feature is a young population that formed in a gaseous outflow that has detached from its natal gas and is falling back toward the galaxy. This result, combined with a companion study (Gingras et al. 2024) tracing nebular emission which presumably cooled from the hot X-ray atmosphere, indicates that star formation is proceeding in a dynamically complex environment resulting from the central galaxy’s motion with respect to the cooling clouds and motion induced by feedback from the central radio jets. In RX J0820.9+0752 intermediate age stars are found in a filament outside of the nucleus with no discernible star formation at the center of the galaxy. All projected galaxies are composed of old stellar populations with deep D4000 breaks and are devoid of detectable warm gas. While in some instances they may be interacting gravitationally with the central galaxy, they cannot have donated the upward of $10^{10} \text{ M}_{\odot}$ of molecular gas found in these systems.

Keywords: Brightest cluster galaxies, Emission nebulae, Galactic stellar populations, Stellar kinematics, Cooling flows, Intracluster medium, AGN host galaxies, Star formation

1. INTRODUCTION

Clusters of galaxies are home to the most massive elliptical galaxies in the Universe. Referred to as brightest cluster galaxies (BCGs), these galaxies sit at the centers of hot, X-ray-emitting atmospheres, with luminosities ranging between 10^{43} and $10^{45} \text{ erg s}^{-1}$ and temperatures of 10^7 – 10^8 K . Under typical central densities of $n_e \gtrsim 10^{-2} \text{ cm}^{-3}$ and cooling times below one Gyr, hot atmospheres are expected to cool radiatively and condense into molecular clouds, eventually fueling star formation (Fabian 1994; Peterson & Fabian 2006; Cavagnolo et al. 2008; Pulido et al. 2018).

Multiphase gas and star formation are commonly observed in cool-core BCGs. Observations reveal co-spatial hot X-ray gas (Cavaliere et al. 1971; Gursky et al. 1971; Sarazin 1986), warm ionized nebular gas at 10^4 K (Heckman 1981; Cowie et al. 1983; Hu et al. 1985; Heckman et al. 1989; Crawford et al. 1999; Hatch et al. 2007; McDonald et al. 2010, 2011a; Olivares et al. 2019; Russell et al. 2019), and cold molecular gas at tens of Kelvin (Lazareff et al. 1989; Edge 2001; Salomé & Combes 2003). Star formation is common in cooling cores, such as in systems like A1835 and the Phoenix cluster with star formation rates (SFRs) of ~ 100 – $700 \text{ M}_{\odot} \text{ yr}^{-1}$ (McDonald et al. 2012, 2019; Calzadilla et al. 2022), although cooling cores typically have SFRs of ~ 1 – 10

$M_{\odot}\text{yr}^{-1}$ (Crawford et al. 1999; O’Dea et al. 2008; McDonald et al. 2011b). These rates are orders of magnitudes lower than what is expected from cooling rates inferred from X-ray observations (McNamara & O’Connell 1989; Fabian 1994; Peterson & Fabian 2006). This discrepancy—commonly referred to as the “cooling flow problem”—highlights the need for feedback mechanisms that regulate cooling (Binney & Tabor 1995; McNamara & Nulsen 2007, 2012; Fabian 2012).

The most viable heating mechanism capable of injecting enough energy to offset cooling is active galactic nuclei (AGN) feedback, where radio jets launched from the central supermassive black hole (SMBH) interact with the surrounding intracluster medium (ICM). These AGN-driven jets can inflate X-ray cavities by displacing $10^7 - 10^{10} M_{\odot}$ of hot gas from its surroundings. The cavities then rise buoyantly through the atmosphere, heating it (Churazov et al. 2001; Bîrzan et al. 2004; McNamara & Nulsen 2007; Rafferty et al. 2006; Pope et al. 2010; Fabian 2012).

AGN-driven jets, and their associated X-ray cavities, not only heat the galaxy’s hot atmosphere but can also trigger localized cooling, eventually leading to star formation (Revaz et al. 2008; Brighenti et al. 2015; McNamara et al. 2016; Donahue & Voit 2022). As X-ray cavities rise buoyantly through the galaxy’s atmosphere, lower entropy gas from the center of the galaxy is uplifted to higher altitudes. This displaced gas encounters a new thermodynamic environment and can undergo thermally unstable cooling, resulting in molecular gas condensation and star formation. This process can also result in gas mixing and in metallicity changes as higher metallicity gas is being displaced away from the center (Revaz et al. 2008; Simionescu et al. 2009; Kirkpatrick et al. 2011; Gaspari et al. 2013; Li et al. 2015; McNamara et al. 2016).

Multiphase gas and star formation are commonly observed in cool core BCGs in a manner consistent with this model. Multiphase gas filaments have been observed in many cooling cores, often trailing rising X-ray cavities (Hu et al. 1985; Heckman et al. 1989; Crawford et al. 1999; Hatch et al. 2007; McDonald et al. 2010).

While the nebular and molecular gas phases in BCGs have been studied extensively, stellar populations have received comparatively less attention. Most studies of stars in BCGs have relied on broadband photometry or long-slit spectroscopy to infer stellar ages, metallicities, and SFRs (Loubser et al. 2009; Pipino et al. 2009; Donahue et al. 2015). These methods provide limited spatial and spectral information and cannot resolve the complex interplay between star formation, stellar kinematics, and AGN-driven processes in cluster cores. As a result, it

remains unclear how newly formed stars are distributed and whether they retain kinematic signatures of their formation—such as infall, rotation, or lifting.

Our observations address these gaps by providing detailed maps of stellar continuum emission, velocities, and star formation ages across the inner tens of kpc in three BCGs with well-characterized cooling flows and multiphase gas (McNamara et al. 2006, 2014; Russell et al. 2016; Vantyghem et al. 2017; Gingras et al. 2024). We obtained detailed observations of the core of the BCGs of RX J0820.9+0752, A1835 and PKS 0745-191 using the Keck Cosmic Web Imager (Morrissey et al. 2018, KCWI) which is mounted on the Keck II telescope. We used KCWI’s integral field spectroscopy (IFS) abilities to obtain high resolution spatial and spectral observations of the three systems discussed in this paper. The high quality KCWI data allows us to distinguish the emission from the nebula and the starlight from the host galaxy.

An earlier paper, Gingras et al. (2024), focused on the nebular gas distribution and kinematics, utilizing the prominent [OII]3726,9 Å emission lines. In this paper we focus on the stellar emission. We analyze the spatial distributions, velocities and ages of the stars in the central tens of kpc of these galaxies. We also compare the dynamics of the stars to those of the multiphase gas and known AGN feedback features: Atacama Large Millimeter/submillimeter Array (ALMA) observations of the molecular gas (McNamara et al. 2014; Russell et al. 2016; Vantyghem et al. 2017, 2019), KCWI observations of the nebular gas (Gingras et al. 2024), and Chandra observations of the X-ray gas and cavities (Hogan et al. 2017b; Pulido et al. 2018; Russell et al. 2019; Vantyghem et al. 2019).

In Section 2 we describe our observations and outline the stellar continuum fitting techniques used. In Section 3 we present and analyse flux, velocity and age maps of the stars for each of our targets (RX J0820.9+0752; Subsection 3.1, A1835; Subsection 3.2, and PKS 0745-191; Subsection 3.3). In Section 4 we summarize the main takeaways from our analysis. Throughout this paper we use a flat Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_m = 0.3$.

2. OBSERVATIONS AND DATA REDUCTION

The central galaxies discussed in this paper were observed using KCWI. While Gingras et al. (2024) focused on the nebular gas properties, this paper investigates stellar dynamics using the same KCWI observations. The observations and most of the data reduction and analysis are identical for both papers. As the current work focuses on stars, we will refrain from discussing

the data reduction and analysis associated with nebular emission, which is discussed in detail in [Gingras et al. \(2024\)](#).

2.1. Observations

In this paper, we discuss our observations of the stellar emission in the cores of three central galaxies using integral field unit (IFU) spectroscopy.¹ For all our targets, we used the KCWI blue low-dispersion (BL) grating and medium slicer, resulting in a field-of-view (FOV) of $16''.5 \times 20''.4$ for each pointing, a spaxel scale of $0''.29 \times 0''.69$ and a spectral resolution of $R = 1800$. All targets use a detector binning of 2×2 . [Table 1](#) lists additional observational parameters for each target.

As the primary goal of our observations was to study the extended gas nebula in the center of these galaxies, the number of pointings, their positions, and the total observing area for each target were selected accordingly. Previous optical observations of our targets, both for stellar and nebular emission, were used to tailor our observations to regions of interest.

2.2. Data reduction

The data were reduced using the KCWI data extraction and reduction pipeline (KDERP) in IDL. KDERP has eight stages including: bias subtraction, gain corrections, cosmic ray removal, correcting atmospheric refraction, scattered light and sky subtraction and flux calibration using a standard star. The scattered light and sky subtraction steps of the data reduction require blank sky images, which are obtained by manually masking emission sources from the images. For each pointing, the corresponding blank sky image was subtracted from the raw observations. For a few pointings where the emission source extends across the entire FOV, blank sky images could not be obtained. In these cases, the blank sky image of a nearby pointing was used. Finally, for each target, the various pointings were resampled onto a grid with spaxel sizes of $0''.29 \times 0''.29$ and summed together to form a mosaic, using routines from the IFSRED library ([Rupke 2014a](#)).

2.3. Stellar continuum fitting

Each spaxel in the reduced mosaics was fitted using the IFSFIT IDL library from [Rupke \(2014b\)](#). All spectra were fitted using both the Penalized Pixel-Fitting

(PPXF) method ([Cappellari & Emsellem 2004](#)) to fit the stellar continuum, and MPFIT ([Markwardt 2009](#)) to fit the emission lines.

In this work, we focus on the stellar continuum fits, where emission lines and known sky lines are masked. We fitted the resulting stellar continuum using the PPXF method from [Cappellari & Emsellem \(2004\)](#). This method uses a linear combination of stellar population synthesis (SPS) models at solar metallicity ([Choi et al. 2016; Byrne & Stanway 2023](#)) and Legendre polynomials. The stellar population models used throughout this paper consist of a set of 43 SPS templates, all with stellar metallicity, which vary in stellar ages between 1 Myr and 9 Gyr. Legendre polynomials are used when fitting the continuum to account for issues remaining after the data reduction process such as atmospheric effects, scattered light, and/or residual features in the stellar continuum. The contribution of each SPS template is taken to be its fractional contribution to the total stellar continuum at $5000 \text{ \AA}$ (rest-frame).

Before fitting each spaxel in our reduced mosaics, we had to define the systemic velocity of each system, which was used as the 0 km s^{-1} speed throughout our analysis. To create a high quality spectrum from which we measured the systemic velocity, the spaxels with the brightest stellar continuum were summed together. The resulting stellar continuum was fitted using the PPXF method previously described. In this case, we used Legendre polynomials of order 30. The stellar velocity obtained from this fit is taken to be the systemic velocity.

However, the stellar continuum fit requires an initial guess for the systemic velocity, which we took from the literature ([Russell et al. 2019](#)). Since the measured stellar velocity depends on the accuracy of the initial guess, we iteratively measured the stellar velocity using the previous result as our initial guess. This process stopped when the uncertainty on the fitted stellar velocity exceeded the change between the values from successive iterations by at least an order of magnitude.

Once a systemic velocity is defined, we fitted each spaxel in our reduced mosaic using the PPXF ([Cappellari & Emsellem 2004](#)) method previously discussed with a Legendre polynomial of order 15.

Both our emission line fits and our continuum fits are corrected for extinction. For the nebular gas, the color excess $E(B-V)_{\text{gas}}$ is measured from the Balmer decrement, using the ratio of the total fluxes (per spaxel) of $H\beta$ to $H\gamma$. We used the extinction curve from [Cardelli et al. \(1989\)](#) for Case B recombination at 10^4 K and $R_V = 3.1$. When either the $H\beta$ or $H\gamma$ flux could not be observed, the median $E(B-V)_{\text{gas}}$ value was used instead. The stellar broadband color excess for the

¹ As part of the same work we observed A262, which contains a circumnuclear disk. Its unusual stellar kinematics will be discussed in an upcoming paper.

Table 1. KCWI Observations

Target	Date	Central wavelength	# of pointings	Total observing time	Seeing	Total FOV	Total extent
	(DD/MM/YYYY)	(Å)		(hrs)	($''$)	($'' \times ''$)	(kpc $\times$ kpc)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
RX J0820.9+0752	14/01/2022	4650	9	2.25	0.9	21×24	44×50
A1835	19/03/2021	5300	6	2	0.8	35×33	141×134
PKS 0745-191	12/02/2021	4650	11	3.67	1.2	26×31	52×61

NOTE—Columns: (1) Target name. (2) Date of KCWI observation. (3) Central wavelength. (4) Number of pointings. (5) Total observing time. (6) Seeing. (7) Total FOV obtained from the different pointings in arcseconds. (8) Same as the previous column but in kpc. This table is a subset of Table 2 presented in [Gingras et al. \(2024\)](#).

stars, $E(B-V)_*$, was obtained from the PPXF fit, which uses the [Calzetti et al. \(2000\)](#) attenuation curve with $R_V = 4.05$. We obtained the value for $E(B-V)_*$ and estimated the 1σ uncertainties using Monte Carlo simulations.

Stellar masses and star formation rates were estimated from the stellar continuum fits. To calculate stellar masses, we used B-band mass-to-light ratios (M/L_B) from the [Bruzual & Charlot \(2003\)](#) stellar population models, which assume solar metallicity and a Salpeter initial mass function. Observed spectra were convolved with a B-band transmission curve using the synphot Python package ([Lim 2020](#)) to derive the B-band luminosity. From the continuum fits, we know the relative contribution of each SPS template at 5000 Å. Since B-band luminosities and mass-to-light ratios were used in these calculations, we took the ratio of the flux at 4420 Å and 5000 Å to get the relative contribution of each template at 4420 Å, which is the central wavelength of the Johnson B-band. The B-band luminosity contribution of each SPS template was then combined with the corresponding M/L_B to calculate the stellar mass of each population. The total stellar mass and SFRs were computed by summing the mass contributions over all templates, using the age of each population to estimate the average SFR over the relevant time interval.

3. RESULTS

Using KCWI integral field spectroscopy we are able to map both the nebular and stellar emission in the cores of our targets. We focus here on the stellar properties, while [Gingras et al. \(2024\)](#) focused on the kinematics of the nebular gas. In this section we analyze the stellar spatial distributions, velocities, and ages in the cores of the central galaxies of RX J0820.9+0752 (Subsection 3.1), A1835 (Subsection 3.2), and PKS 0745-191 (Subsection 3.3).

3.1. RX J0820.9+0752

The center of RX J0820.9+0752 is highly asymmetric, which has been seen across multiple wavelength bands ([Bayer-Kim et al. 2002](#); [Vantyghem et al. 2019](#)). Its nebular and molecular gas lie ~ 20 kpc northwest of the peak stellar emission ([Bayer-Kim et al. 2002](#); [Salomé & Combes 2004](#); [Vantyghem et al. 2017, 2019](#); [Olivares et al. 2019](#)). RX J0820.9+0752 is also known for its massive $10^{10} M_\odot$ reservoir of cold molecular gas ([Vantyghem et al. 2017](#)) and for its peculiar morphology, with two blue clumpy arcs north-east of the central galaxy with strong and dusty line emission ([Bayer-Kim et al. 2002](#)).

From top to bottom, [Figure 1](#) shows the stellar continuum flux map, stellar central velocity map (v_*) and differences in the nebular gas velocity with respect to the stellar velocity map ($v_{50}^{\text{[OIII]}} - v_*$). We detect stellar emission in a region spanning roughly 14 kpc across. The total stellar luminosity is $2.3 \times 10^{43} \text{ erg s}^{-1}$ between observed wavelengths of 3700 – 5650 Å.

The top panel of [Figure 1](#) shows two distinct peaks corresponding to the two galaxies within our FOV: the main/brightest galaxy, taken to be the center of the system, and a secondary galaxy located ~ 7.8 kpc south-east.

In the middle panel of [Figure 1](#) positive velocities correspond to redshifted stars (with respect to the systemic velocity) and negative velocities are blueshifted. The solid grey lines outline the continuum flux, with contours showing 20%, 40% and 80% of the peak continuum flux. The velocities of the stars in the nucleus are close to 0, by definition. The continuum flux-weighted mean stellar velocity is $\sim 50 \text{ km s}^{-1}$. We use flux-weighted velocities to estimate the average velocity of stars or gas within a region. We define this as:

$$\bar{v} = \frac{\sum_i v_i \times f_i}{\sum_i f_i} \quad (1)$$

Table 2. Properties of Regions of Interest

Target	Region	$E(B-V)_{\text{gas}}$	$E(B-V)_*$	$D_n(4000)$	Young	Intermediate age	Old	Depletion timescale
		(mag)	(mag)		(%)	(%)	(%)	(Myr)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
RX J0820.9+0752	Main galaxy	0.2 ± 0.2	0.00 ± 0.01	2.11	0.15	8.5	91.5	
	Secondary galaxy	-	0.12 ± 0.03	2.68	2	8	89	~ 7000
	Blue arc	0.46 ± 0.09	0.04	1.59	2	52	45	
A1835	East	0.3 ± 0.1	0.04 ± 0.02	1.42	45	34	21	
	Central	0.5 ± 0.2	0.00 ± 0.01	1.46	30	53	17	~ 500
	West	0.4 ± 0.4	0.00 ± 0.03	1.54	15	36	48	
PKS 0745-191	Main galaxy	0.83 ± 0.08	0.31 ± 0.03	1.65	27	11	62	~ 625
	Secondary galaxy	-	0.23 ± 0.05	2.70	7	0	93	

NOTE—(3) Nebular broadband color excess obtained using the Case B extinction curve from [Cardelli et al. \(1989\)](#) with $R_V=3.1$ and the ratio of $H\beta/H\gamma$. (4) Stellar broadband color excess obtained from continuum fits using the extinction curve from [Calzetti et al. \(2000\)](#) using $R_V=4.05$. Uncertainties show the 1σ errors obtained from 100 Monte Carlo iterations. (5) Balmer break index ([Balogh et al. 1999](#)), which is the ratio of the blue continuum band flux (3750-3850 Å) to the red continuum band flux (4150-4250 Å): $\int_{3750}^{3850} F_\nu(\lambda) d\lambda / \int_{4150}^{4250} F_\nu(\lambda) d\lambda$. These bands were chosen for their lack of emission lines in our three targets. (6)–(8) Relative contribution of young (≤ 10 Myr), intermediate age (10 Myr–1 Gyr) and old (> 1 Gyr) stars to the stellar continuum. The distribution of stellar ages within a region is obtained from the relative contribution of each SPS template to the starlight fit at a rest-frame wavelength of 5000 Å (see [Subsection 2.3](#)). (9) Depletion timescale: Time for star formation to deplete the current molecular gas reservoir in each galaxy. For RX J0820.9+0752, the average SFR over the past 500 Myr is used. For A1835 and PKS 0745-191, the average SFR over the past 10 Myr is used.

where v is the velocity and f_i is the flux within the i th spaxel of any given region. The stellar velocity map shows two redshifted regions, one north and one south, with $v_* \sim +175$ km s $^{-1}$ and $v_* \sim +130$ km s $^{-1}$, respectively. The southern redshifted region coincides with the position of the secondary galaxy. Two slightly blueshifted regions lie to the east and west of the nucleus.

The bottom panel of [Figure 1](#) compares the median nebular gas velocity to the velocity of the stars in each spaxel. The median velocity of the [OII] doublet is used for the nebular gas velocity as it is the brightest emission line for our three targets.² The dashed dotted ellipse shows the position of a low significance X-ray cavity ([Vantyghem et al. 2019](#)).

The $v_{50}^{\text{[OII]}} - v_*$ map shows little blueshifted gas with respect to the stars. [Gingras et al. \(2024\)](#) detected a bulk motion between the nebular gas and the central stars of $+150$ km s $^{-1}$ in RX J0820.9+0752, which is seen by the overall redshifting of the nebular gas in the bottom panel of [Figure 1](#). The largest velocity difference between the nebular gas and the stars is seen west of the nucleus, where $v_{50}^{\text{[OII]}} - v_* \sim +175$ to $+300$ km s $^{-1}$. The stars in this region are slightly blueshifted by ~ -35 km s $^{-1}$ (see central panel), whereas the nebular gas is redshifted. North of this region the stars have similar

velocities as the nebular gas, with $v_{50}^{\text{[OII]}} - v_* \sim +40$ km s $^{-1}$.

[Figure 2](#) focuses on three regions of interest within our FOV: the main galaxy, the secondary galaxy, and the blue continuum arc identified by [Bayer-Kim et al. \(2002\)](#). An HST image of the blue arc is shown in the upper right of [Figure 2](#) ([Bayer-Kim et al. 2002](#); [Vantyghem et al. 2017](#)). The grey region in [Figure 2](#) shows the stellar continuum morphology while the colored regions show the spaxels used to create spatially-integrated spectra of the three regions of interest.

[Table 2](#) lists various properties of the regions shown in [Figure 2](#), including their broadband color excess from both nebular and stellar emission, the Balmer break index, and the relative contribution of young (≤ 10 Myr), intermediate age (10 Myr–1 Gyr) and old (> 1 Gyr) stars to the stellar continuum flux. The uncertainties on $E(B-V)$ quoted in [Table 2](#) reflect only the statistical errors from the fit. The true uncertainties are likely larger due to systematic effects. [Table 2](#) also lists the depletion timescales for each system, which is the time required to exhaust the galaxy’s molecular gas reservoir at their current SFR.

The main galaxy has little dust, with $E(B-V) \sim 0$ both for the gas and for the stars. This is also the case for the secondary galaxy, with $E(B-V)_* = 0.12 \pm 0.03$. Following [Martis et al. \(2016\)](#), we consider a region to be dusty if $E(B-V) \geq 0.3$. On the other hand, the nebular gas associated with the blue continuum arc is

² See [Gingras et al. \(2024\)](#) for more explanation on the emission line fitting methodology.

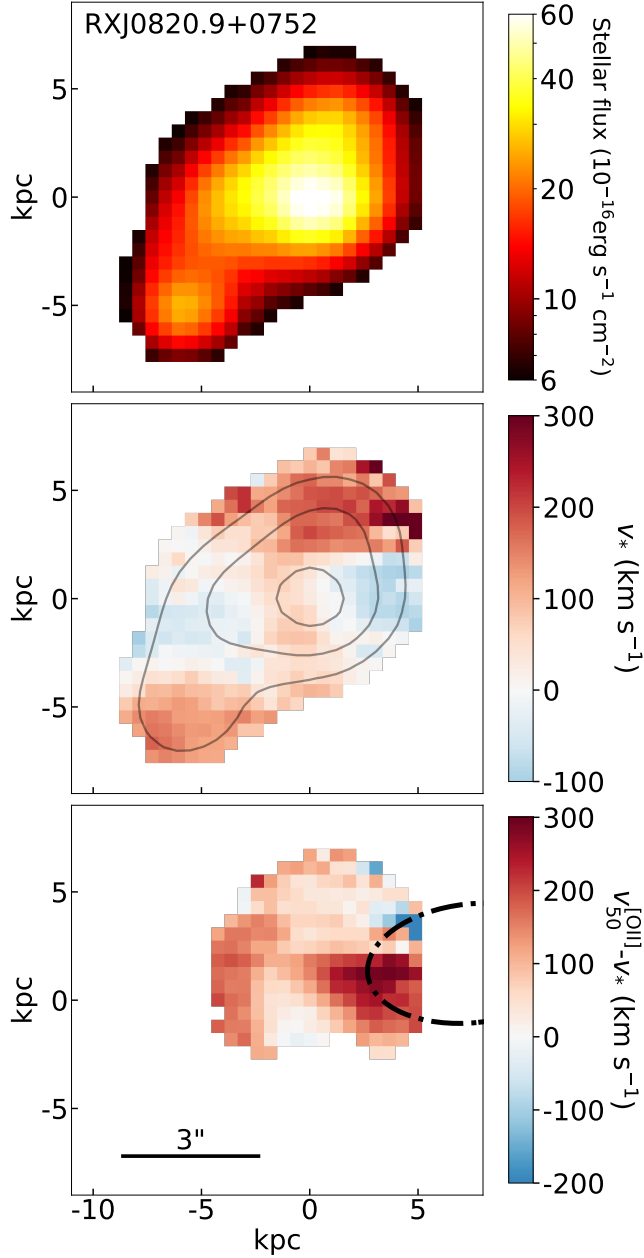


Figure 1. Maps of stellar properties of the central galaxy in RX J0820.9+0752. Top: Integrated stellar flux map for rest-frame wavelengths of 3300 – 5100 Å. Only spaxels with stellar fluxes of at least $5 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ are shown. Center: Stellar velocity map. The grey lines show stellar flux contours corresponding to 20%, 40% and 80% of the maximum stellar flux per spaxel. Bottom: Velocity of the nebular gas with respect to the stellar velocity. Unless specified otherwise, the velocity of the nebular gas is taken to be the total [OII]3726,9 Å emission line median velocity ($v_{50}^{\text{[OII]}}$). The black dash-dotted ellipse shows the position of the X-ray cavity observed by Vantyghem et al. (2019).

dusty, with $E(B-V)_{\text{gas}} = 0.46$. This is consistent with observations by Bayer-Kim et al. (2002) which measure $E(B-V)$ between 0.3–0.7 in the various star formation knots of the blue arcs.

Figure 3 shows the spatial distributions of the fractions of young, intermediate age and old stars. These fractions are determined by measuring the contribution of the SPS models in each age bin to the fitted continuum. Similarly, Figure 4 maps the *luminosity* emitted by stars of different ages. The white contours show the ALMA CO(3-2) emission in the core of RX J0820.9+0752 (Vantyghem et al. 2017).

The spectra in Figure 2 show that the stellar populations in the main and projected galaxies are old. They have strong Balmer breaks and lack Balmer absorption lines. This is also seen in Figure 3 and Figure 4 where almost all of the stellar emission, 92% for the main galaxy and 89% for the secondary galaxy, is emitted by stars older than 1 Gyr.

On the other hand, the blue arc has a significant intermediate age stellar population, with half of the starlight coming from intermediate age stars and half from old stars (presumably background stars). This is confirmed by the spatially-integrated spectrum of the blue arc in Figure 2, which shows strong Balmer absorption lines. As the main and secondary galaxies are dominated by older stars, it is unlikely that the gas and young stars in the blue arc were stripped from either galaxy. The stars likely cooled out of the surrounding gas, with gravitational interactions between the two galaxies potentially triggering the cooling process. The bottom panel of Figure 1 shows similar velocities between the stars and the nebular gas in the blue arc, which further supports the scenario that the stars in the blue arc cooled out of the nebular gas.

Figure 4 shows that the $10^{10} M_{\odot}$ reservoir of molecular gas partially overlaps with the blue arc (Vantyghem et al. 2017), making it a possible fuel source for the long-lived star formation. The intermediate age stellar population in this blue arc has a mass of almost $7 \times 10^8 M_{\odot}$, with a star formation rate of $1.4 M_{\odot} \text{ yr}^{-1}$ over the past 500 Myr. With a molecular gas reservoir of $10^{10} M_{\odot}$ (Vantyghem et al. 2017) and a SFR of $1.4 M_{\odot} \text{ yr}^{-1}$, this star formation has ample molecular gas to consume, with a depletion timescale of ~ 7 Gyr, indicating that this star forming region can continuously sustain itself if fed by the nearby molecular gas.

The top panels of Figure 3 and Figure 4 show a dearth of stars younger than 10 Myr throughout the center of RX J0820.9+0752. Only $\sim 2\%$ of the starlight in the blue arc comes from younger stars. This indicates that the strong line emission in the blue arc is unlikely

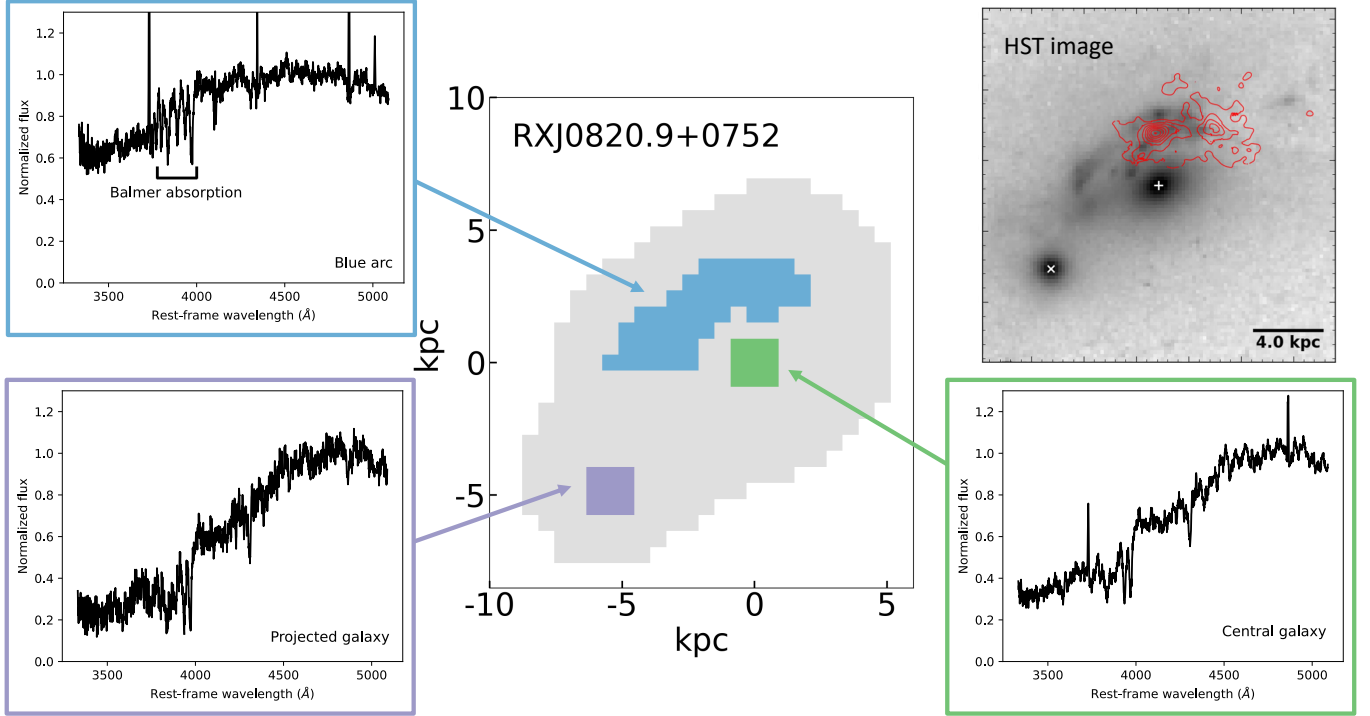


Figure 2. Spectra of three regions in RX J0820.9+0752: $0.5''$ (radius) around the nucleus (green), $0.5''$ around the nucleus of the secondary galaxy (purple) and the arc of young stars previously seen in Hubble Space Telescope observations (Bayer-Kim et al. 2002; Vantyghem et al. 2017). The upper right panel shows the HST image of RX J0820.9+0752 as shown in Vantyghem et al. (2017). The red contours show the distribution of CO(3-2) from ALMA. The grey region in the central panel shows the morphology of the stellar emission as plotted in the top panel of Figure 1. The colored regions in the 2D map show the spaxels included in each integrated spectrum. The vertical axis of the spectra shows the normalized flux where the flux is normalized by the average flux between $4700 \text{ \AA}$ and $4800 \text{ \AA}$, allowing us to compare the continuum shapes of different regions.

to have been caused by photoionization from young O and B type stars. A different ionization mechanism, such as shocks or cosmic ray heating (Pfrommer 2008; Ruszkowski et al. 2008), is most likely responsible for the widespread nebular emission in RX J0820.9+0752.

3.2. A1835

A1835 is a strong cooling core cluster undergoing powerful radio-mechanical AGN feedback (McNamara et al. 2014). Its central galaxy has a SFR of $\sim 100 - 180 M_{\odot} \text{ yr}^{-1}$ in the inner $\sim 35 \text{ kpc}$ and contains $\sim 5 \times 10^{10} M_{\odot}$ of molecular gas in the central $\sim 10 \text{ kpc}$.

Analogous to Figure 1, Figure 5 maps the stellar continuum flux, stellar velocity, and nebular gas velocity with respect to the stars. The top panel shows the stellar flux in the inner region of interest here; the larger FOV, which includes eight projected galaxies, is shown in Appendix A. There, we show that none of the projected galaxies appear to be impacting the dynamics of the central galaxy. Therefore, Figure 5 only includes the central region where nebular emission is observed. Five projected galaxies are present in this main region and are seen as stellar flux peaks in the top panel of Figure 5.

The total stellar luminosity shown in the top panel of Figure 5 between observed wavelengths of $4300 - 6300 \text{ \AA}$ is $1.9 \times 10^{44} \text{ erg s}^{-1}$.

The central panel of Figure 5 shows that the stellar velocities in the core of A1835 lie between $\sim -400 \text{ km s}^{-1}$ and $\sim +200 \text{ km s}^{-1}$, with velocities increasing (more redshifted) from east to west. Although there is a stellar velocity gradient from east to west, the stellar velocities are not consistent with rotation, since the blueshifted and redshifted velocities differ in magnitudes by hundreds of km s^{-1} . The bottom panel of Figure 5 shows that most of the nebular gas is redshifted with respect to the stars, with an overall redshift of $\sim 150 \text{ km s}^{-1}$ (Gingras et al. 2024). The main feature in this velocity map is the region east of the nucleus where the velocity difference between the nebular gas and the stars is $\sim +600 \text{ km s}^{-1}$. This corresponds to the highlighted region in the stellar velocity map, where the stars are blueshifted by $\sim 300 \text{ km s}^{-1}$.

Figure 6 shows spatially-integrated spectra of three regions of interest in the core of the central galaxy of A1835. These three regions were selected using the stellar velocity map: eastern blueshifted region (blue), cen-

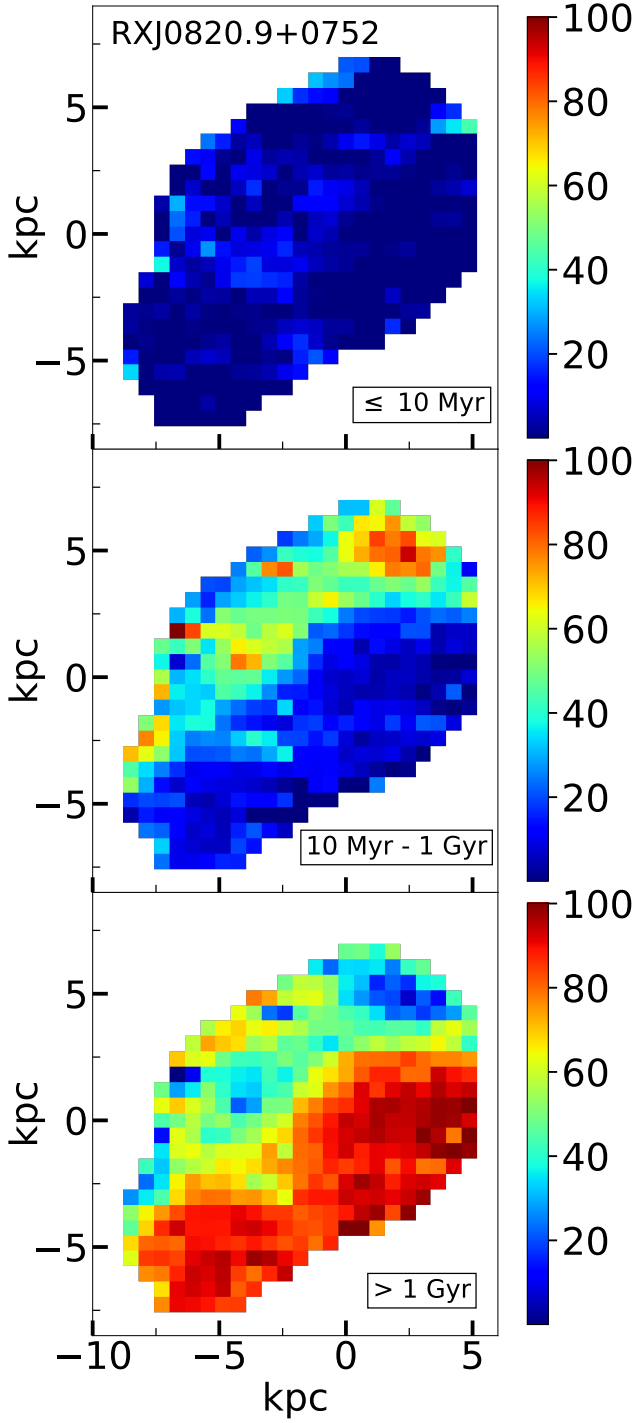


Figure 3. Distributions of stellar ages in RX J0820.9+0752. The colorbar represents the fraction of the stellar flux emitted by young (≤ 10 Myr), intermediate (10 Myr – 1 Gyr) and old (> 1 Gyr) stellar populations.

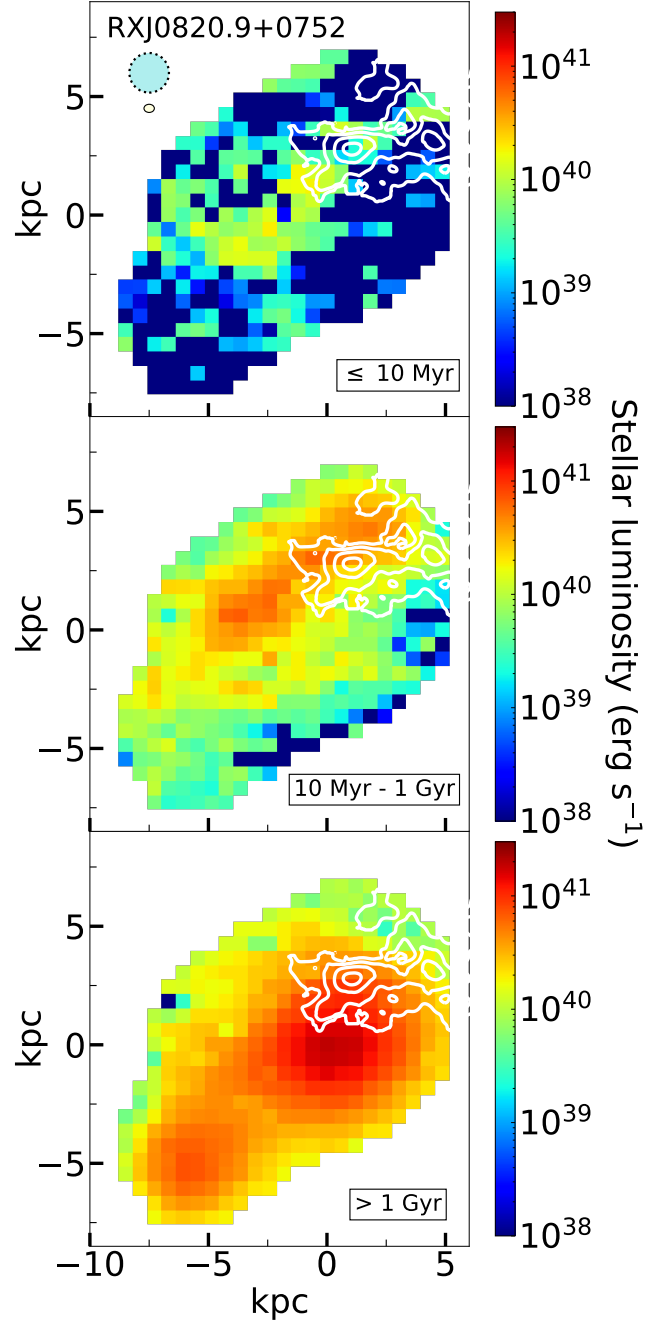


Figure 4. Stellar luminosity distributions in the central galaxy of RX J0820.9+0752 for young (top panel), intermediate age (middle panel) and old (bottom panel) stars. The white contours show ALMA CO(3–2) emission flux, which represent 10%, 20%, 40%, and 80% of the maximum CO(3–2) flux (Vantyghem et al. 2017). The solid line ellipse shows the beam size of the ALMA CO(3–2) observations and the dashed circle shows the seeing of our KCWI observations.

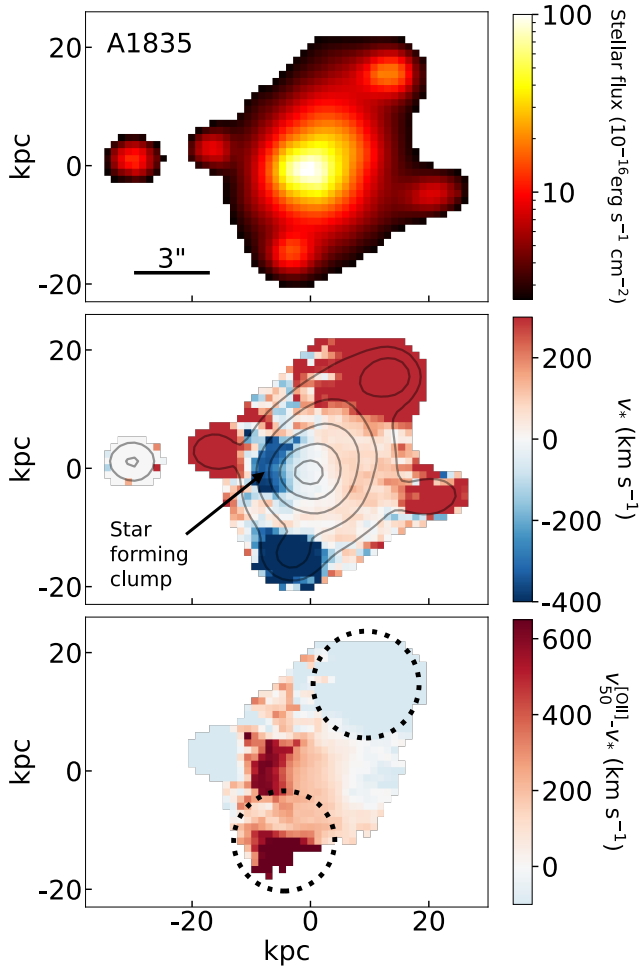


Figure 5. Stellar properties maps for the central galaxy of A1835. Top: Stellar continuum flux map for rest-frame wavelengths of 3435–5035 Å. Only spaxels with stellar fluxes of at least $2.5 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ are included. Middle: Median stellar velocity map where grey contours show stellar fluxes of 5%, 10%, 20%, 40% and 80% of the maximum stellar flux per spaxel. Bottom: Velocity of the nebular gas with respect to the stellar velocity. The black dotted ellipses show the positions of X-ray cavities (McNamara et al. 2006; Olivares et al. 2019; Russell et al. 2019).

tral region (green), and western redshifted region (magenta). Table 2 lists their properties. The nebular emission in the center of A1835 is dusty, with all three central regions having $E(B-V)_{\text{gas}} \geq 0.3$. These values are consistent within 1σ with those listed in Crawford et al. (1999).

Figure 7 shows the spatial distribution of the relative fractions of young, intermediate age, and old stars in the core of A1835. Similarly, Figure 8 maps the luminosity of young, intermediate age and old stars. Both figures show extended young and intermediate age stellar populations spanning a radius of 15 – 20 kpc around the

nucleus. This is clearly seen in the spatially-integrated spectra in Figure 6 which all have strong Balmer absorption lines. This indicates long-lived star formation over a large region surrounding the nucleus.

Throughout our FOV, we estimate an average SFR of $40 \text{ M}_{\odot} \text{ yr}^{-1}$ for the past 1 Gyr, with an increased SFR of $100 \text{ M}_{\odot} \text{ yr}^{-1}$ in the past 10 Myr. These star formation rates are consistent with those measured by Crawford et al. (1999) and McNamara et al. (2006). As discussed in Appendix A, all the projected galaxies have old stellar populations, making it unlikely that stripped gas from these projected galaxies fueled this star formation. Therefore the galaxy’s massive reservoir of molecular gas and the starburst it fuels likely cooled from the surrounding hot atmosphere. Fueled by $5 \times 10^{10} \text{ M}_{\odot}$ of molecular gas (McNamara et al. 2014), a SFR of $100 \text{ M}_{\odot} \text{ yr}^{-1}$ implies a depletion timescale of $\sim 500 \text{ Myr}$. In order to sustain the current SFR of $100 \text{ M}_{\odot} \text{ yr}^{-1}$, the reservoir of molecular gas fueling this star formation will need to be replenished by newly-formed cool gas.

Figure 8 shows that the young and intermediate age stars spatially overlap with the detected molecular gas. If the more spatially extended distribution of young and intermediate age stars roughly traces the full distribution of molecular gas, then additional extended molecular gas may exist below our detection limit. Gingras et al. (2024) made a similar argument using the distribution of $[\text{OII}]\lambda 3726,9 \text{ Å}$, inferring a possible M_{mol} of more than $10^{11} \text{ M}_{\odot}$.

Figure 7 and Table 2 show differences in the stellar age distributions in the core of A1835. While all three regions in Figure 6 have less than half of their emission coming from stars older than 1 Gyr, both the Balmer break indices and the fractions of young, intermediate age and old stars show a gradient in stellar ages from east to west.

3.2.1. Young Stars Forming in an Outflow?

Figure 6 shows a large clump of star formation 5 – 10 kpc east of the nucleus. This accounts for 7 – 10% of the starlight from the central region. Its spectrum, in Figure 6, shows strong nebular line emission and strong Balmer absorption features consistent with a young but aging population. Its stellar mass for stars younger than 10 Myr is $1.65 \times 10^8 \text{ M}_{\odot}$, which implies an average SFR of $16.5 \text{ M}_{\odot} \text{ yr}^{-1}$ over the past 10 Myr. It has an average SFR over the past Gyr of $3.5 \text{ M}_{\odot} \text{ yr}^{-1}$, showing a recent increase in the region’s SFR.

Figure 5 shows that the velocities of the stars and the nebular gas projected along the same line-of-sight are offset in velocity by $\simeq 600 \text{ km s}^{-1}$. The flux-weighted stellar velocity is blueshifted with respect to the central

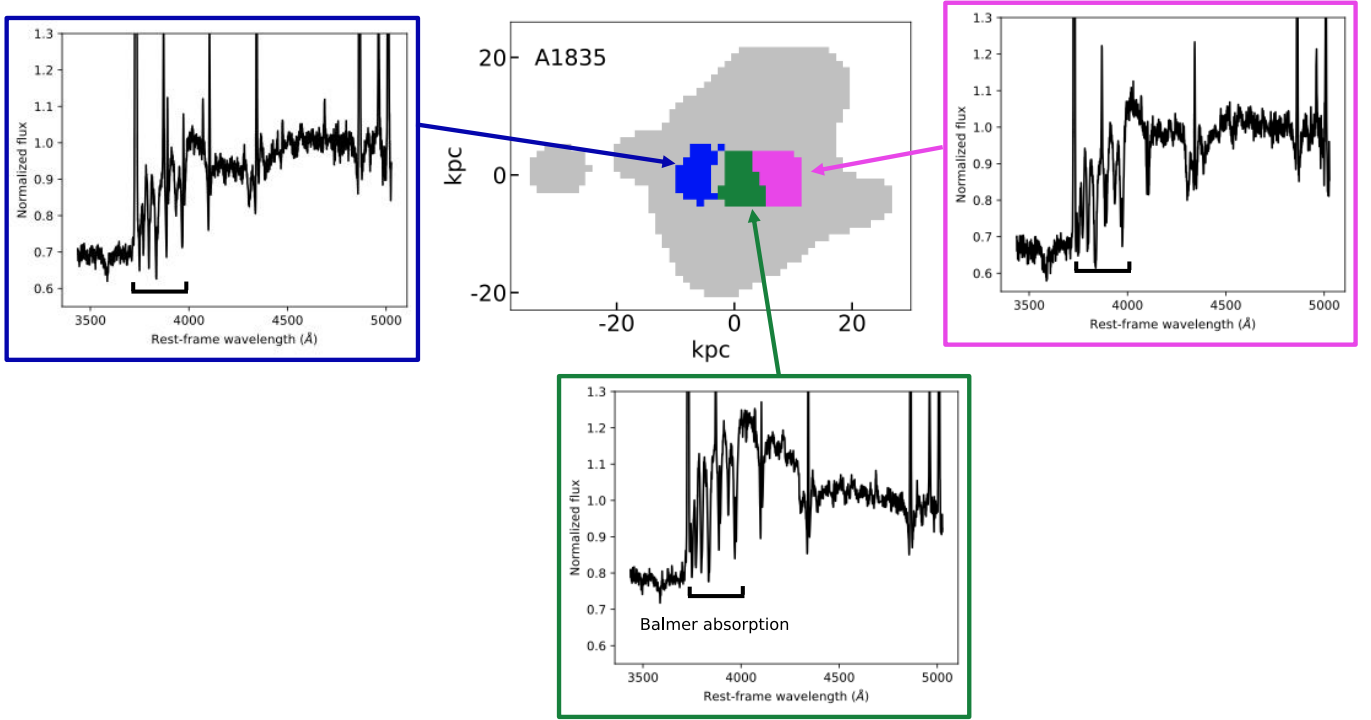


Figure 6. Spectra of three central regions in A1835. The grey region shows the spatial distribution of the stellar emission as in the top panel of Figure 5.

galaxy by -280 km s^{-1} while the nebular gas is redshifted by $\approx 307 \text{ km s}^{-1}$. Molecular gas emitting in the CO(1-0) line with a mass of $5 \times 10^9 - 1 \times 10^{10} M_{\odot}$ is observed close to this line-of-sight. The molecular gas, which is shown in Figure 8 (McNamara et al. 2014), is redshifted with respect to the galaxy by $\sim 500 \text{ km s}^{-1}$, receding slightly faster than the nebular gas. These large velocity differences would suggest at first glance that the gas and stars along the line-of-sight are unrelated. However, it would be surprising if such a large, coherent region of recent star formation formed with no surrounding gas to fuel it. We therefore explore the possibility that the two are related, but that the stars have decoupled dynamically from their birth clouds.

The high relative speeds of the system could be explained naturally by tidal or ram-pressure stripping from a flyby galaxy or as debris in a late-stage merger. While these possibilities cannot be excluded outright, they present several issues. Firstly, none of the eight galaxies projected along the line-of-sight within 60 kpc of the central galaxy contain emission lines or blue populations capable of donating upward of $10^{10} M_{\odot}$ of molecular gas, nor are there clear signs of tidal tails and debris linked to these galaxies. All appear to be old red ellipticals.

A late-stage merger is another possibility. However a galaxy, likely a spiral, containing so much molecular gas would be rare in a cluster at this redshift. Finding its

way into the center of the cluster where few star-forming galaxies reside would be equally unlikely (Dressler 1980; Dressler et al. 1997; Balogh et al. 2004; Boselli & Gavazzi 2006).

The enormous amount of gas has been shown to almost certainly originate from cooling (McNamara et al. 2014; Gingras et al. 2024). Therefore in this context, we should consider how such a high-speed population would form. Gas condensing into stars at large radii and falling inward is a possibility. The velocity differences between the stars and gases could arise as the stars decoupled from the gas and began falling ballistically with the trailing gases descending more slowly due to ram pressure drag. However, this model would have great difficulty accounting for the relative magnitudes and signs of the velocities.

We instead focus on the more likely possibility that the stars formed in a nebular gas outflow driven by the central radio jets and X-ray bubbles.

Gingras et al. (2024) showed that nebular gas velocities in this region are consistent with a bipolar outflow in the same direction as the clumps of gas and star formation. The young stars may have formed in this outflow over the past 10 Myr but have since decoupled from their birth clouds.

This scenario is shown in the left panel of Figure 9. It shows the time evolution of outflowing nebular gas as

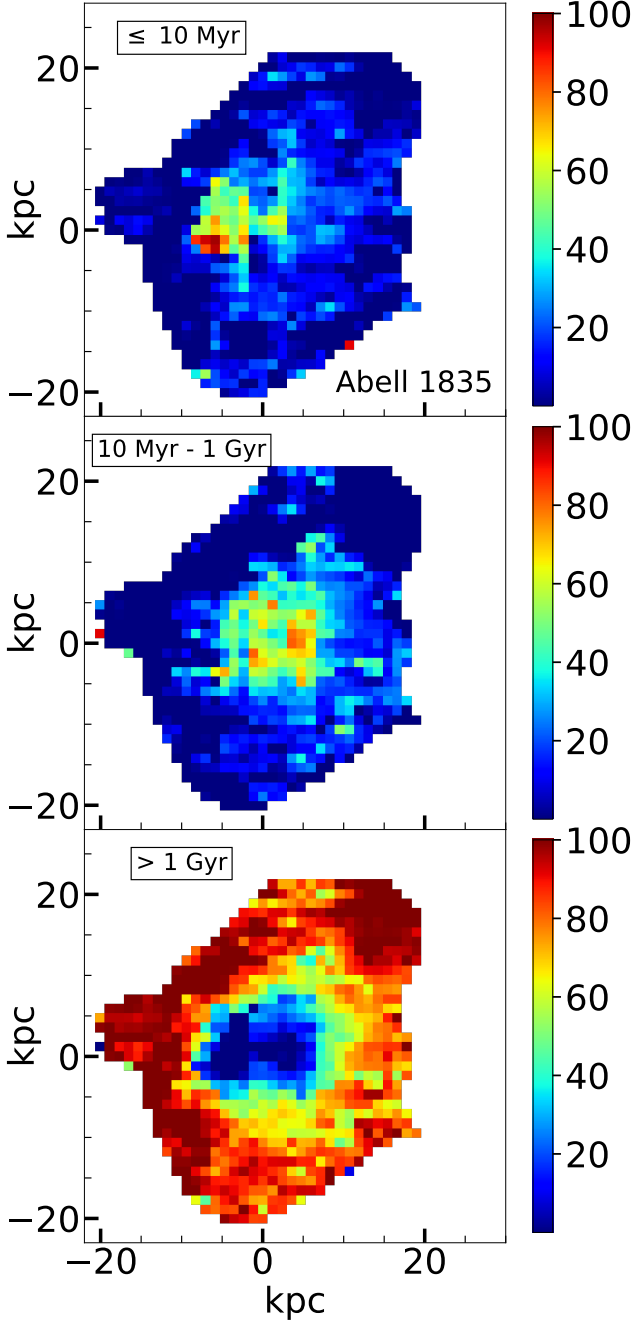


Figure 7. Distributions of stellar ages in the central galaxy of A1835. The colorbar represents the fraction of the stellar flux emitted by young (≤ 10 Myr), intermediate age (10 Myr – 1 Gyr) and old (> 1 Gyr) stars.

it is driven in the wake of an X-ray cavity, cooling and ultimately forming stars. While X-ray cavities may be uplifting the outflowing gas, we have yet to identify the mechanism responsible for driving the gaseous outflow. The nebular gas outflow which spatially coincides with the young star clump does not have a detected X-ray cavity associated with it. However, there are numerous

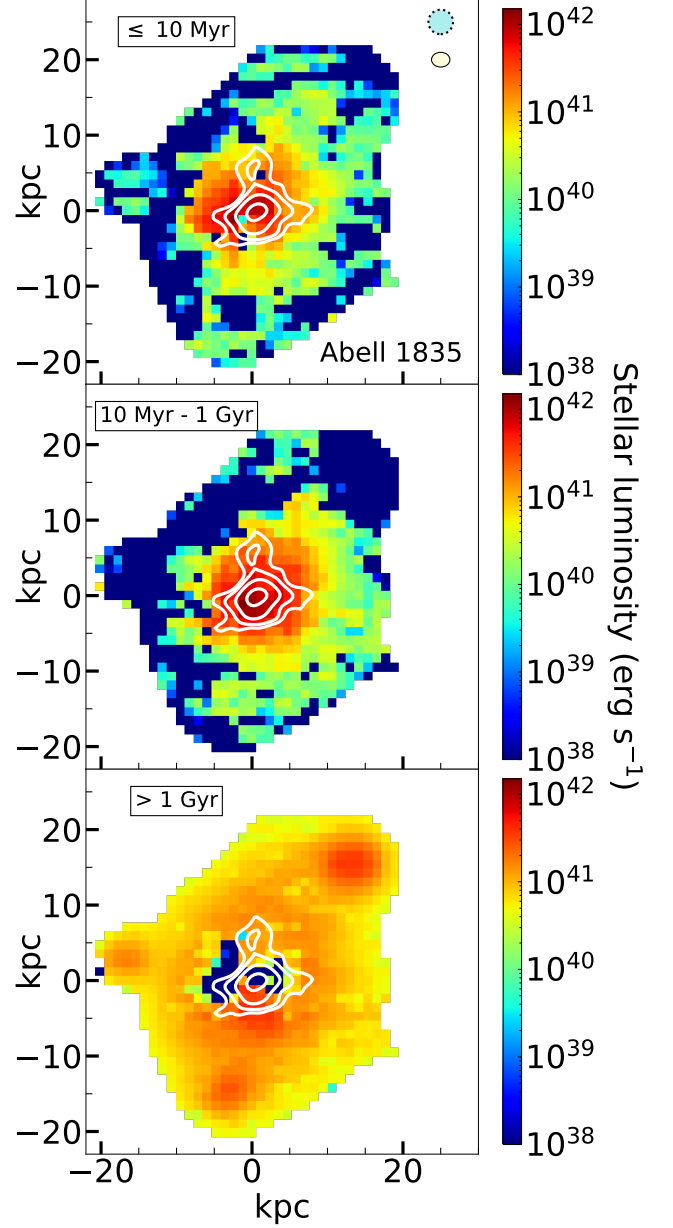


Figure 8. Stellar luminosity distributions for young (top panel), intermediate age (middle panel) and old (bottom panel) stars in the central galaxy of A1835. The white contours show ALMA CO(3–2) emission flux, which represent 10%, 20%, 40%, and 80% of the maximum CO(3–2) flux (McNamara et al. 2014). The solid line ellipse shows the beam size of the ALMA CO(3–2) observations and the dashed circle shows the seeing of the KCWI observations.

reasons why X-ray cavities may not be detected. They can become difficult to detect due to buoyant rise, deformation and mass entrainment which reduces the X-ray contrast, projection effects, and low signal-to-noise (Enßlin & Heinz 2002; Bîrzan et al. 2004; Brüggen et al. 2009).

If we assume that the forming stars are initially moving with the nebular gas outflow at a line-of-sight velocity of 307 km s^{-1} , we can calculate the timescale on which they will reverse their motion and ultimately fall ballistically towards the central AGN at velocities of -280 km s^{-1} . Hogan et al. (2017b) and Pulido et al. (2018) modeled the gravitational potential of A1835 as a combination of an isothermal and NFW potential and inferred a total mass of $\sim 9 \times 10^{11} M_{\odot}$ within a radius of 7 kpc from the Chandra X-ray centroid. Hogan et al. (2017a) shows that this gravitational potential model gives reliable total enclosed masses at the radius studied here. Knowing the total enclosed mass and the distance from the center, we calculate a gravitational acceleration at 7 kpc of $-2.5 \times 10^{-12} \text{ km s}^{-2}$, which is used throughout these calculations. The right panel of Figure 9 shows how the altitude and the line-of-sight velocities of the nebular gas and the most recently formed stars evolve with time. The forming/newly-formed stars are assumed to be falling ballistically without drag, from an initial line-of-sight velocity of $+307 \text{ km s}^{-1}$ to a final observed velocity of -280 km s^{-1} . Therefore, knowing their initial and final velocities, as well as the gravitational potential (Hogan et al. 2017b; Pulido et al. 2018), we can calculate the star-forming clump’s position and velocity throughout this process, as shown in Figure 9. It takes roughly 10 Myr for the newly-formed stars to decouple from the nebular gas outflow and infall towards the galaxy center at a line-of-sight velocity of -280 km s^{-1} . The dark red dotted line in Figure 9 shows the motion of the outflowing nebular gas, which is still being uplifted. The line-of-sight velocity of the nebular gas is taken to be constant at $+307 \text{ km s}^{-1}$ (see Figure 15 of Gingras et al. 2024).

Throughout this analysis, we assume that the outflowing/inflowing nebular gas and stars are moving at a 45° angle with respect to our line-of-sight, such that their velocities are $\sqrt{2}v_{\text{LOS}}$. The age of the young stars is similar to the time since the decoupling began, implying they could have formed out of the gaseous outflow, decoupled from it, and be now raining back towards the central AGN.

The blueshifted stellar velocities imply that the stars falling inward began their descent on the far side of the galaxy. The positive velocities of the nebular and molecular gas indicate they continue to be driven, moving outward on the far side of the galaxy. Their velocity difference indicates that they as well may have separated due to differential ram pressure forces or different coupling with rising bubbles or jet.

A similar mechanism was cited to explain the outflow population in the Seyfert galaxy IRAS F23128–5919

(Maiolino et al. 2017). In that system stars formed roughly 500 pc from the nucleus in a molecular outflow driven by nuclear radiation pressure. The star formation rate in the outflow population is $\sim 30 M_{\odot} \text{ yr}^{-1}$ representing roughly one quarter of the star formation rate of the entire system. The outflow population and nebular gas velocities differ by $150 - 350 \text{ km s}^{-1}$. Therefore, apart from their acceleration mechanisms, the two systems are similar. Additionally, in A1835 it is occurring on a somewhat larger scale.

As seen in Figure 9, we expect to see a spatial separation between the nebular gas and the star forming clump as the stars decouple from the outflowing gas. The nebular gas steadily rises away from the central AGN from $\sim 6.9 \text{ kpc}$ to $\sim 11.5 \text{ kpc}$, while the star-forming clump peaks at a projected distance barely above 8 kpc and then turns around and falls back close to its starting point. This predicts a spatial offset in the sky-plane between the outflowing nebular gas and the now infalling stars of about 4.3 kpc after $\approx 10 \text{ Myr}$. However, as seen in the bottom panel of Figure 5, the outflowing gas and the blueshifted stars spatially overlap in our observations, forming a region where the velocity difference between the nebular gas and the stars reaches 600 km s^{-1} . Since our observations of A1835 have a seeing of 3.25 kpc and both the outflowing gas and the infalling stars extend over regions larger than the expected spatial offset, we expect the gaseous outflow and the infalling stars to spatially overlap along our line-of-sight. Follow-up observations with the Hubble Space telescope or the James Webb Space Telescope should be able to detect this spatial offset if present. Overall, the observed distributions and kinematics of the young stars and nebular gas in this region are consistent with a scenario where infalling stars formed out of a nebular gas outflow driven by the central AGN.

A similar scenario may be occurring in the Perseus cluster’s nebula centred on NGC 1275. Canning et al. (2010, 2014) observe that the young blue stars are spatially offset from their parent filaments by $\sim 0.5 - 3.5 \text{ kpc}$ in the outskirts of the nebula. In this instance many are oriented close to the sky plane allowing for clear spatial segregation.

While we cannot exclude other explanations with certainty, the scenario proposed here has precedent in other systems and in simulations. Revaz et al. (2008) and Gaspari et al. (2012) proposed that masses of low entropy gas far in excess of the mass of the outflow population observed in A1835 are being lifted in the bubble updrafts. This process may accelerate the cooling process which would explain the filaments of cold gas and star formation often found in cooling flows (McNamara et al.

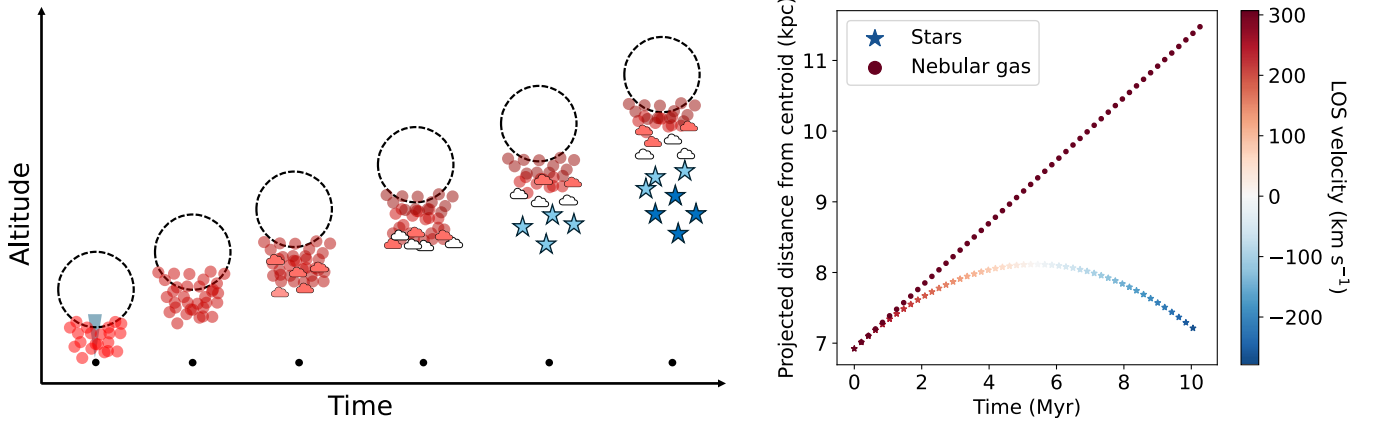


Figure 9. Left: Diagram of the young stars forming in an outflow scenario that is discussed in Subsubsection 3.2.1. The change of colors, from red to blue, denotes the change in line-of-sight velocity from redshifted to blueshifted. Right: Time evolution of the projected distance from the central AGN to the outflowing nebular gas and to the star-forming clump discussed in Subsubsection 3.2.1. The colorbar shows the change in the line-of-sight velocity of the newly-formed stars.

2016). The question, raised earlier by Maiolino et al. (2017), is how important this process may be in galaxy formation and assembly.

3.3. PKS 0745-191

PKS 0745–191 is an archetypal cool cluster core with powerful radio emission (Baum & O’Dea 1991), two known X-ray cavities, significant star formation of $\sim 17 M_{\odot} \text{ yr}^{-1}$ and $\sim 5 \times 10^9 M_{\odot}$ of cold molecular gas distributed in three filaments (O’Dea et al. 2008; Russell et al. 2016).

Figure 10 maps the stellar flux, stellar velocity, and nebular gas velocity with respect to the stars. The stellar flux map shows two peaks corresponding to the central galaxy and a secondary galaxy. The galaxies are separated by a projected distance of ~ 8.5 kpc and with a radial velocity difference of 34 km s^{-1} . We detect stellar emission within a radius of ~ 8 kpc around the brightest spaxel, for a total stellar luminosity of $1.8 \times 10^{43} \text{ erg s}^{-1}$.

We do not observe ordered motion in the v_* map of PKS 0745–191 as in RX J0820.9+0752 and A1835. The range of velocities spanned by the stars is also smaller in the center of this galaxy than in the other two. In addition, other than the bulk motion seen in the nebular gas with respect to the stars, no striking features in the $v_{50}^{\text{[OII]}} - v_*$ map are seen.

Figure 11 shows the integrated spectra for the central and projected galaxies and the spaxels used for each spectrum. Their properties are listed in Table 2. The two galaxies have very different stellar populations, as clearly seen in their spectra. The central galaxy has ongoing star formation, with almost 40% of its starlight coming from young or intermediate age stars. The stellar emission from the projected galaxy almost exclu-

sively comes from older stars. This indicates that the cool gas in the central galaxy is unlikely to have been stripped from the other galaxy within our FOV.

The color excesses listed in Table 2 indicate significant dust extinction in this system. Contrary to our other targets, PKS 0745–191 has substantial galactic extinction, with $E(B-V) = 0.45 \pm 0.01$ (Schlegel et al. 1998). As the $E(B-V)_*$ value for the secondary galaxy is less than what is expected from galactic extinction, the secondary galaxy has little to no dust. Nebular emission in the central galaxy is dusty with $E(B-V)_{\text{gas}} = 0.83 \pm 0.08$ mag. This includes both the intrinsic and the galactic extinction. Even after removing the effects from galactic extinction, the intrinsic $E(B-V)_{\text{gas}}$ is ~ 0.38 . The nebula in the central region of PKS 0745–191 is dusty, consistent with earlier observations (Predehl & Schmitt 1995).

Figure 12 maps the starlight fraction coming from young, intermediate age, and old stars in the core of PKS 0745–191, while Figure 13 shows the luminosity emitted by young, intermediate age and old stars. These figures show that most of the starlight comes from stars older than 1 Gyr. The top and central panels of Figure 13 show higher luminosities from young and intermediate age stars in the central region, roughly aligned along the east-south and north-west axis. This aligns with the X-ray cavities’ axis and overlaps with the system’s large molecular gas filaments (Russell et al. 2016). Within our FOV, we measure a SFR of almost $3 M_{\odot}$ per year for the past billion years with an increase in SFR to $8 M_{\odot} \text{ yr}^{-1}$ in the last 10 Myr. With $\sim 5 \times 10^9 M_{\odot}$ of cold molecular gas (Russell et al. 2016) and a star formation rate of $8 M_{\odot} \text{ yr}^{-1}$, the depletion timescale is ~ 625 Myr. As was the case for A1835, cooling must replenish the

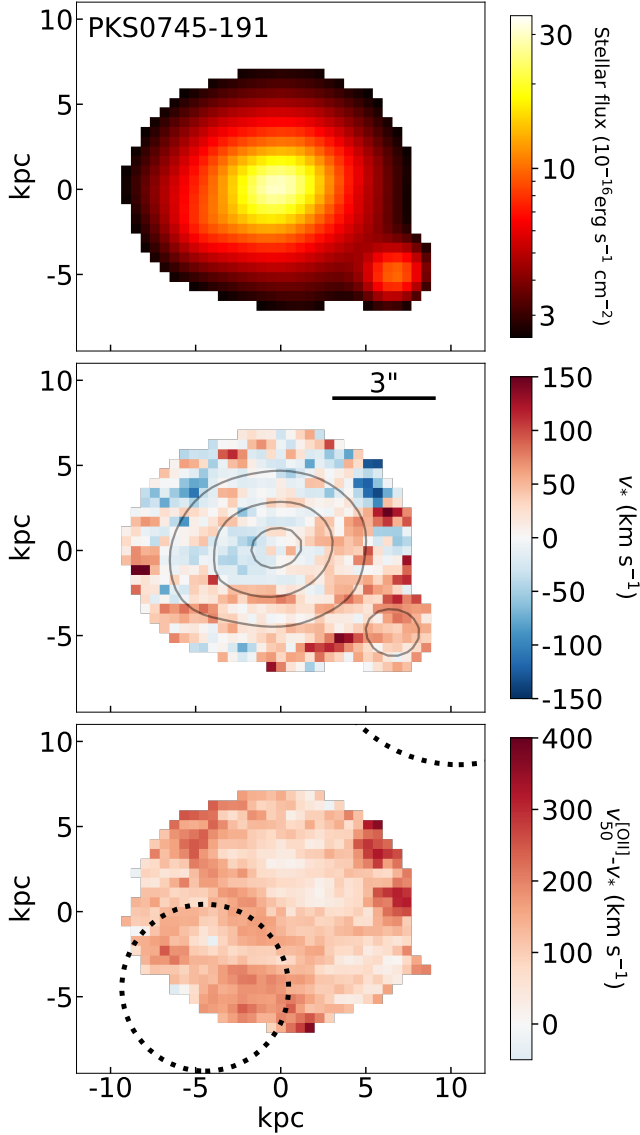


Figure 10. Maps of stellar properties in the central galaxy of PKS 0745–191. Top: Integrated stellar continuum flux map (for a wavelength range between 3356 – 5017 Å.), with a lower stellar flux threshold of $2.5 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$. Middle: Median stellar velocity map. The grey contours identify 20%, 40% and 80% of the maximum stellar flux per spaxel. Bottom: Median velocity of the nebular gas (from [OII] emission) with respect to the stellar velocity. The black dotted ellipses show the positions of X-ray cavities within our FOV (Sanders et al. 2014; Russell et al. 2019).

reservoir of molecular gas in PKS 0745-191 to sustain star formation.

4. SUMMARY

KCWI observations of the central galaxies in RX J0820.9+0752, A1835 and PKS 0745–191 offer new insights into AGN feedback and star formation in cool core clusters. By mapping the stellar continuum flux, line-of-

sight stellar velocities, and stellar ages across the inner tens of kpc, we explore how starlight encodes the history of AGN-regulated cooling and feedback processes in these three systems.

These systems were selected for their strong cooling cores. Each shows distinct stellar dynamics and evolutionary histories. Our conclusions for each central galaxy can be summarized as follows:

- RX J0820.9+0752: The system’s blue arc is dominated by stellar emission from intermediate age stars, challenging previous interpretations that photoionization from recent star formation caused the ionization of the cooling nebula. Both galaxies’ old stellar populations are inconsistent with the idea that the system’s massive reservoir comes from stripping gas from either galaxy. Instead, it is consistent with the gas cooling from the surrounding hot atmosphere, potentially triggered by gravitational effects of galaxy interactions.
- A1835: The inner region of the central galaxy of A1835 has significant star formation, with young and intermediate age stars being detected up to ~ 20 kpc away from the nucleus. With almost $4 \times 10^{10} M_{\odot}$ of stars formed in the last Gyr, A1835 has long-lived star formation. East of the nucleus, we find a blueshifted clump of young stars which supports the presence of stimulated AGN feedback in this system. The kinematics of the stars and that of the nebular gas are consistent with stars cooling out of an outflow and raining back down towards the central AGN.
- PKS 0745-191: We focus on two galaxies in the center of PKS 0745-191. The secondary galaxy is almost exclusively comprised of stars older than 1 Gyr. The stellar population of the central galaxy is more nuanced, although most of the stellar emission also comes from old stars. Some young and intermediate age stars are seen in the core, broadly overlapping with the known molecular gas filaments (Russell et al. 2016). Stellar emission from young stars is roughly aligned along the X-ray cavities axis, indicating that AGN feedback likely plays a role in stimulating star formation in the core of PKS 0745-191.

All three systems contain significant reservoirs of cooling gas and show evidence of nearby galaxies within our field of view. However, these projected galaxies are dominated by old stellar populations, inconsistent with recent or ongoing star formation. This rules out the possibility that the observed cooling gas was stripped from

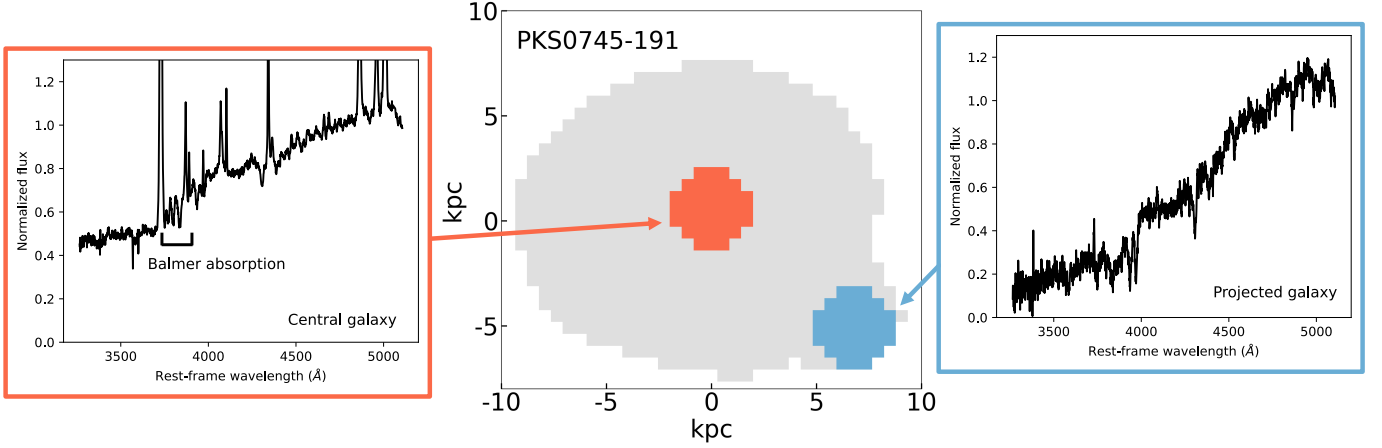


Figure 11. Spectra of the nuclear region of the BCG and the projected galaxy for PKS 0745–191: $1''$ around the nucleus of the BCG (red) and $1''$ around the nucleus of the projected galaxy (blue). The grey region shows the spatial distribution of the stellar emission as in the top panel of Figure 10.

these galaxies. Instead, our results support a scenario in which the cooling gas and subsequent star formation originated in situ, condensing directly from the hot intracluster medium.

In all three galaxies, there is spatial overlap between the youngest stars and the observed molecular gas, supporting the idea that star formation is fueled by this gas (Pulido et al. 2018; Olivares et al. 2019; Russell et al. 2019).

RX J0820.9+0752 shows little to no recent star formation, with its blue arc dominated by intermediate-age stars (30–500 Myr). In contrast, A1835 and PKS 0745–191 have significant populations of young stars (≤ 10 Myr) in their cores, suggesting more recent star formation activity. This difference may reflect varying feedback conditions: both A1835 and PKS 0745–191 host powerful AGN outbursts that can trigger localized cooling and star formation through cavity-driven uplift. The abundance of intermediate-age stars in RX J0820.9+0752 suggest an earlier event triggering cooling, possibly caused by galaxy interactions, with no evidence of ongoing or recent star formation.

Their stellar kinematics also differ. A1835 shows coherent stellar motion with an east–west velocity gradient, while PKS 0745–191 lacks clear dynamical structure. This may reflect differences in stellar populations: A1835’s core is dominated by younger stars, which can retain kinematic signatures of recent feedback or interactions, while PKS 0745–191’s stellar emission is mostly from older stars that trace the bulk dynamics of the galaxy.

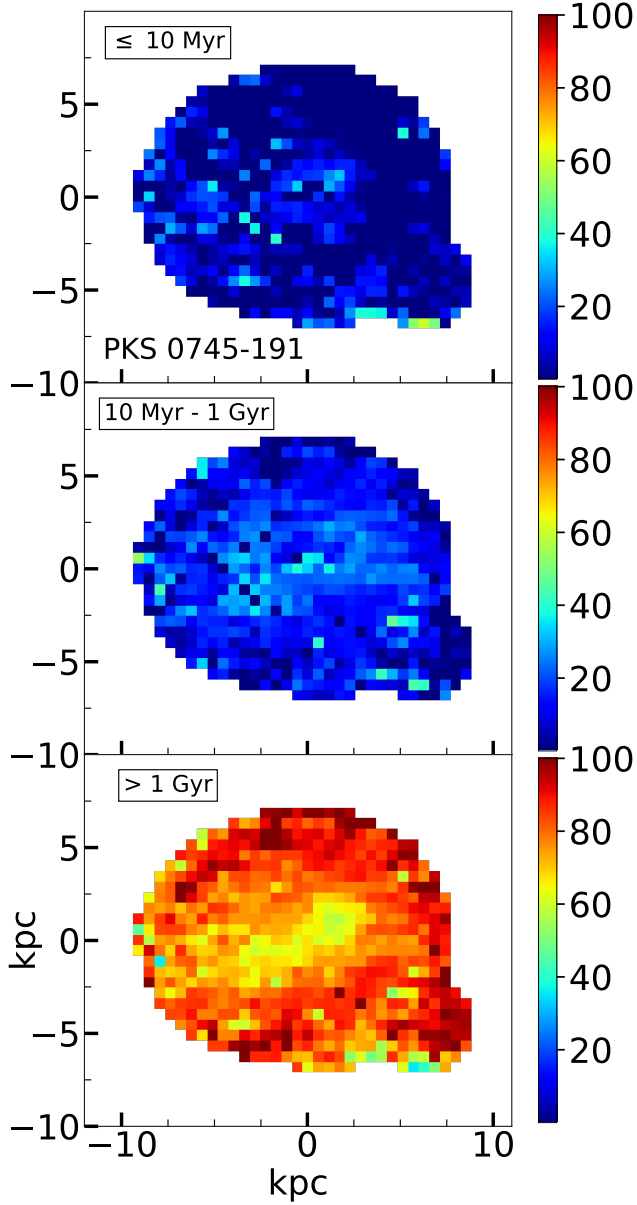
In A1835’s blueshifted clump, where young and intermediate age stars dominate, we are effectively measuring the motion of recently formed stars. In PKS 0745–191,

the overwhelming contribution from old stars masks any potential kinematic signature of younger populations. Future work using multi-component stellar velocity fitting methods will be needed to disentangle the dynamics of young stars in PKS 0745–191 and assess their role in AGN feedback-driven inflows or outflows.

The data presented here were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The observatory was made possible by the financial support of the W. M. Keck Foundation. We wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. We thank David Rupke for his invaluable help in analyzing the Keck observations using the IFSFIT pipeline. B.R.M acknowledges support from the Natural Sciences and Engineering Council of Canada and the Canadian Space Agency Space Science Enhancement Program. A. L. C. acknowledges support from the Ingrid and Joseph W. Hibben endowed chair at UC San Diego.

Facilities: Keck:II

Software: Astropy (Astropy Collaboration et al. 2013, 2018, 2022), Python (Van Rossum & Drake 2009), Numpy (van der Walt et al. 2011; Harris et al. 2020), Matplotlib (Hunter 2007), Scipy (Virtanen et al. 2020),



pPXF (Cappellari 2012, 2017), IFSRED (Rupke 2014a), IFSFIT (Rupke 2014b; Rupke et al. 2017)

Figure 12. Spatial distributions of stellar ages in the central galaxy of PKS 0745–191. The colorbar represents the fraction of stellar flux emitted by young (≤ 10 Myr), intermediate age (10 Myr – 1 Gyr) and old (> 1 Gyr) stars.

APPENDIX

A. TOTAL FOV OF A1835

Figure 14 shows the total flux map for the total FOV observed for A1835. Apart from the central galaxy, we observed an additional eight projected galaxies. Each of the nine galaxies are identified in Figure 14 and the corresponding spatially-integrated spectrum is shown. The spaxels for each galaxy were summed and fitted using the technique described in Subsection 2.3. Most of the projected galaxies have old stellar populations with prominent Balmer breaks.

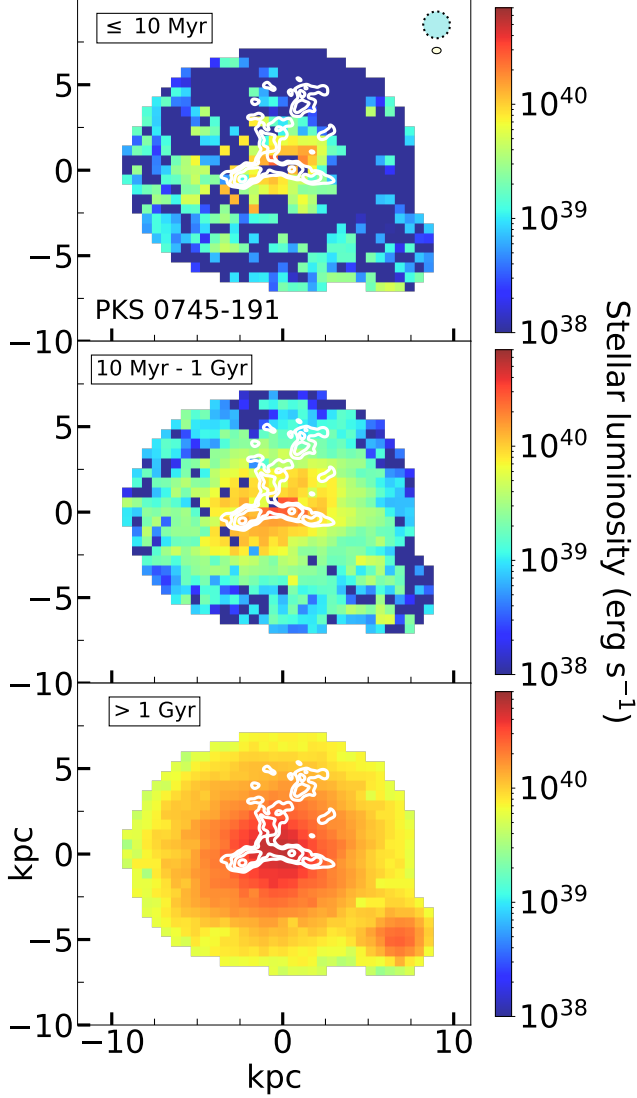


Figure 13. Stellar luminosity distributions in the central galaxy of PKS 0745–191 for young (top panel), intermediate age (middle panel) and old (bottom panel) stars. The white contours show ALMA CO(3–2) emission flux, with contours of 10%, 20%, 40%, and 80% of the maximum CO(3–2) flux (Russell et al. 2016). The solid line ellipse shows the beam size of the ALMA CO(3–2) observation and the dashed circle shows the seeing of the KCWI observations.

Since galaxy interactions can significantly affect galaxy dynamics, we compare the galaxies’ positions and kinematics to investigate possible interactions with the central galaxy and its surrounding atmosphere. Table 3 lists the stellar redshifts measured from the resulting fits as well as listing each galaxy’s relative velocity to the central galaxy. The percentage of the total starlight and the stellar luminosity within $1''$ around each galaxy’s brightest spaxel are also listed. The galaxy numbers correspond to the numbers shown in the upper right of each integrated spectrum in Figure 14.

The thousand km s^{-1} velocity differences listed in Table 3 are inconsistent with interactions between the projected galaxies and the central galaxy. Only one projected galaxy, identified as Galaxy 8 in Figure 14, has similar velocity as the central galaxy. While their stellar velocities differ by only $\sim 20 \text{ km s}^{-1}$, their projected separation of more than 60 kpc makes tidal interactions between the two objects very unlikely. Moreover, since the projected galaxies have old

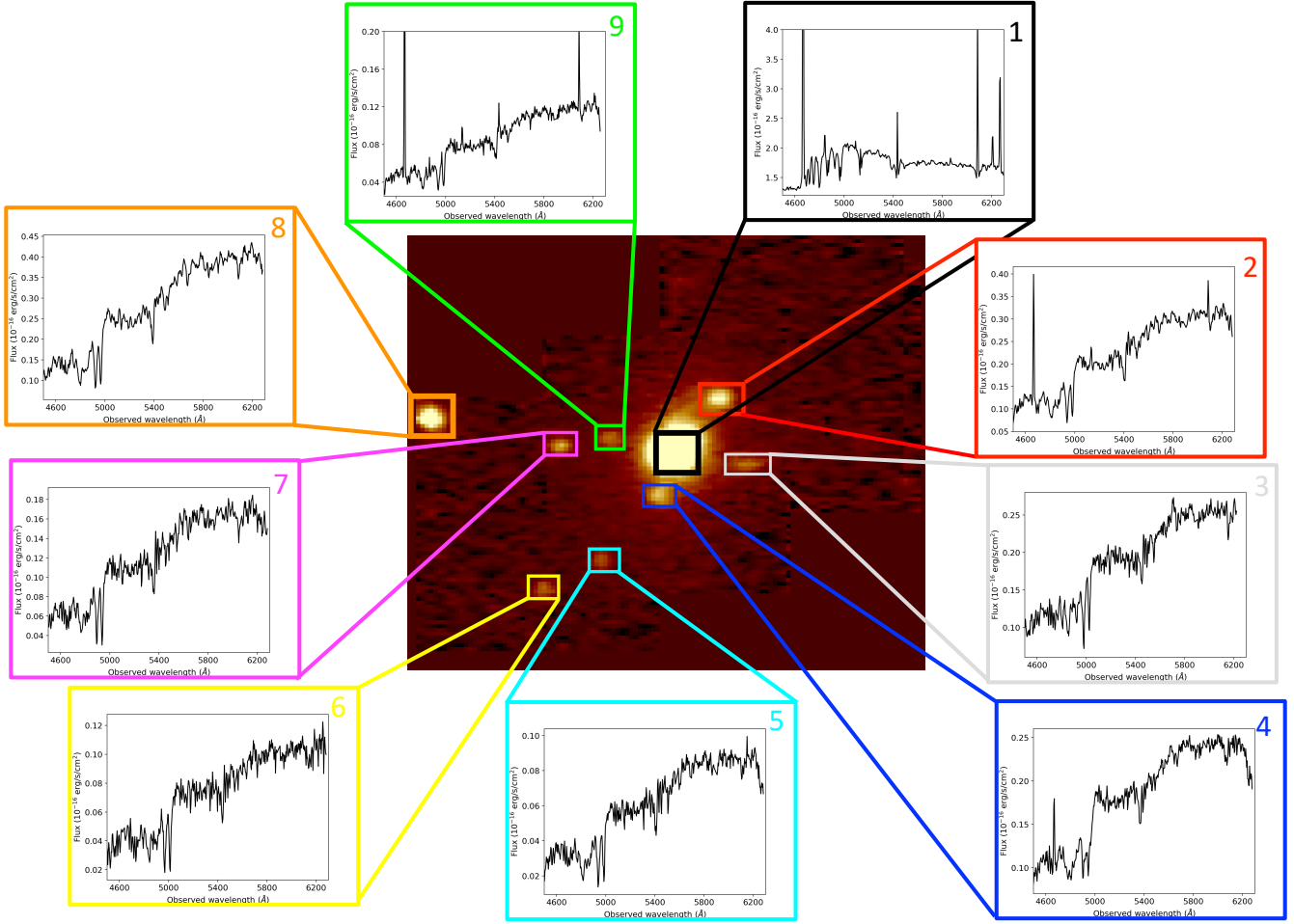


Figure 14. Total flux map of the mosaic image of A1835. Nine galaxies are present in the image, the BCG (1) and eight other galaxies which are projected along our line-of-sight (2-9). The integrated spectra for each boxed region are shown.

stellar populations, it is unlikely that they are interacting with the central galaxy, as some star formation or younger stellar population would be expected in that case. Therefore, while the central galaxy of A1835 is accompanied by eight projected galaxies within our FOV, it does not appear to be interacting with any of them. The A1835 cluster is known to have a velocity dispersion of $\sim 1500 \text{ km s}^{-1}$, making most of the projected galaxies likely members of the cluster.

REFERENCES

- Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, *A&A*, 558, A33, doi: [10.1051/0004-6361/201322068](https://doi.org/10.1051/0004-6361/201322068)
- Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, *AJ*, 156, 123, doi: [10.3847/1538-3881/aabc4f](https://doi.org/10.3847/1538-3881/aabc4f)
- Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., et al. 2022, *ApJ*, 935, 167, doi: [10.3847/1538-4357/ac7c74](https://doi.org/10.3847/1538-4357/ac7c74)
- Balogh, M. L., Baldry, I. K., Nichol, R., et al. 2004, *ApJL*, 615, L101, doi: [10.1086/426079](https://doi.org/10.1086/426079)
- Balogh, M. L., Morris, S. L., Yee, H. K. C., Carlberg, R. G., & Ellingson, E. 1999, *ApJ*, 527, 54, doi: [10.1086/308056](https://doi.org/10.1086/308056)
- Baum, S. A., & O’Dea, C. P. 1991, *MNRAS*, 250, 737, doi: [10.1093/mnras/250.4.737](https://doi.org/10.1093/mnras/250.4.737)
- Bayer-Kim, C. M., Crawford, C. S., Allen, S. W., Edge, A. C., & Fabian, A. C. 2002, *MNRAS*, 337, 938, doi: [10.1046/j.1365-8711.2002.05969.x](https://doi.org/10.1046/j.1365-8711.2002.05969.x)
- Binney, J., & Tabor, G. 1995, *MNRAS*, 276, 663, doi: [10.1093/mnras/276.2.663](https://doi.org/10.1093/mnras/276.2.663)

Table 3. Stellar velocities and luminosities of the galaxies in the FOV of our observations of A1835.

Galaxy	Redshift	Relative velocity	Stellar flux	Luminosity
		(km/s)	(%)	(erg/s)
(1)	(2)	(3)	(4)	(5)
1	0.2513	0	22.27	4.63×10^{43}
2	0.2550	1113	4.00	8.34×10^{42}
3	0.2657	4304	1.85	3.85×10^{42}
4	0.2461	-1566	3.15	6.55×10^{42}
5	0.2557	1323	0.91	1.90×10^{42}
6	0.2625	3371	0.99	2.07×10^{42}
7	0.2440	-2189	2.08	4.32×10^{42}
8	0.2512	-20	5.16	1.07×10^{43}
9	0.2557	1321	1.70	3.53×10^{42}

NOTE— (1) Galaxy number, as indicated in Figure 14. (2) Redshift of the galaxy. (3) Relative velocity of the galaxy with respect to the BCG. (4) Percentage of the total starlight within a radius of $1''$ around the galaxy’s brightest spaxel. (5) Luminosity within a radius of $1''$.

- Birzan, L., Rafferty, D. A., McNamara, B. R., Wise, M. W., & Nulsen, P. E. J. 2004, *ApJ*, 607, 800, doi: [10.1086/383519](https://doi.org/10.1086/383519)
- Boselli, A., & Gavazzi, G. 2006, *PASP*, 118, 517, doi: [10.1086/500691](https://doi.org/10.1086/500691)
- Brighenti, F., Mathews, W. G., & Temi, P. 2015, *ApJ*, 802, 118, doi: [10.1088/0004-637X/802/2/118](https://doi.org/10.1088/0004-637X/802/2/118)
- Brüggen, M., Scannapieco, E., & Heinz, S. 2009, *MNRAS*, 395, 2210, doi: [10.1111/j.1365-2966.2009.14684.x](https://doi.org/10.1111/j.1365-2966.2009.14684.x)
- Bruzual, G., & Charlot, S. 2003, *MNRAS*, 344, 1000, doi: [10.1046/j.1365-8711.2003.06897.x](https://doi.org/10.1046/j.1365-8711.2003.06897.x)
- Byrne, C. M., & Stanway, E. R. 2023, *MNRAS*, 521, 4995, doi: [10.1093/mnras/stad832](https://doi.org/10.1093/mnras/stad832)
- Calzadilla, M. S., McDonald, M., Donahue, M., et al. 2022, *ApJ*, 940, 140, doi: [10.3847/1538-4357/ac9790](https://doi.org/10.3847/1538-4357/ac9790)
- Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, *ApJ*, 533, 682, doi: [10.1086/308692](https://doi.org/10.1086/308692)
- Canning, R. E. A., Fabian, A. C., Johnstone, R. M., et al. 2010, *MNRAS*, 405, 115, doi: [10.1111/j.1365-2966.2010.16474.x](https://doi.org/10.1111/j.1365-2966.2010.16474.x)
- Canning, R. E. A., Ryon, J. E., Gallagher, J. S., et al. 2014, *MNRAS*, 444, 336, doi: [10.1093/mnras/stu1191](https://doi.org/10.1093/mnras/stu1191)
- Cappellari, M. 2012, pPXF: Penalized Pixel-Fitting stellar kinematics extraction, Astrophysics Source Code Library, record ascl:1210.002
- . 2017, *MNRAS*, 466, 798, doi: [10.1093/mnras/stw3020](https://doi.org/10.1093/mnras/stw3020)
- Cappellari, M., & Emsellem, E. 2004, *PASP*, 116, 138, doi: [10.1086/381875](https://doi.org/10.1086/381875)
- Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, *ApJ*, 345, 245, doi: [10.1086/167900](https://doi.org/10.1086/167900)
- Cavagnolo, K. W., Donahue, M., Voit, G. M., & Sun, M. 2008, *ApJL*, 683, L107, doi: [10.1086/591665](https://doi.org/10.1086/591665)
- Cavaliere, A. G., Gursky, H., & Tucker, W. H. 1971, *Nature*, 231, 437, doi: [10.1038/231437a0](https://doi.org/10.1038/231437a0)
- Choi, J., Dotter, A., Conroy, C., et al. 2016, *ApJ*, 823, 102, doi: [10.3847/0004-637X/823/2/102](https://doi.org/10.3847/0004-637X/823/2/102)
- Churazov, E., Brüggen, M., Kaiser, C. R., Böhringer, H., & Forman, W. 2001, *ApJ*, 554, 261, doi: [10.1086/321357](https://doi.org/10.1086/321357)
- Cowie, L. L., Hu, E. M., Jenkins, E. B., & York, D. G. 1983, *ApJ*, 272, 29, doi: [10.1086/161259](https://doi.org/10.1086/161259)
- Crawford, C. S., Allen, S. W., Ebeling, H., Edge, A. C., & Fabian, A. C. 1999, *MNRAS*, 306, 857, doi: [10.1046/j.1365-8711.1999.02583.x](https://doi.org/10.1046/j.1365-8711.1999.02583.x)
- Donahue, M., & Voit, G. M. 2022, *PhR*, 973, 1, doi: [10.1016/j.physrep.2022.04.005](https://doi.org/10.1016/j.physrep.2022.04.005)
- Donahue, M., Connor, T., Fogarty, K., et al. 2015, *ApJ*, 805, 177, doi: [10.1088/0004-637X/805/2/177](https://doi.org/10.1088/0004-637X/805/2/177)
- Dressler, A. 1980, *ApJ*, 236, 351, doi: [10.1086/157753](https://doi.org/10.1086/157753)
- Dressler, A., Oemler, Jr., A., Couch, W. J., et al. 1997, *ApJ*, 490, 577, doi: [10.1086/304890](https://doi.org/10.1086/304890)
- Edge, A. C. 2001, *MNRAS*, 328, 762, doi: [10.1046/j.1365-8711.2001.04802.x](https://doi.org/10.1046/j.1365-8711.2001.04802.x)
- Enßlin, T. A., & Heinz, S. 2002, *A&A*, 384, L27, doi: [10.1051/0004-6361:20020207](https://doi.org/10.1051/0004-6361:20020207)
- Fabian, A. C. 1994, *ARA&A*, 32, 277, doi: [10.1146/annurev.aa.32.090194.001425](https://doi.org/10.1146/annurev.aa.32.090194.001425)
- . 2012, *ARA&A*, 50, 455, doi: [10.1146/annurev-astro-081811-125521](https://doi.org/10.1146/annurev-astro-081811-125521)
- Gaspari, M., Ruszkowski, M., & Oh, S. P. 2013, *MNRAS*, 432, 3401, doi: [10.1093/mnras/stt692](https://doi.org/10.1093/mnras/stt692)

- Gaspari, M., Ruszkowski, M., & Sharma, P. 2012, *ApJ*, 746, 94, doi: [10.1088/0004-637X/746/1/94](https://doi.org/10.1088/0004-637X/746/1/94)
- Gingras, M.-J., Coil, A. L., McNamara, B. R., et al. 2024, *ApJ*, 977, 159, doi: [10.3847/1538-4357/ad822a](https://doi.org/10.3847/1538-4357/ad822a)
- Gursky, H., Kellogg, E., Murray, S., et al. 1971, *ApJL*, 167, L81, doi: [10.1086/180765](https://doi.org/10.1086/180765)
- Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, *Nature*, 585, 357, doi: [10.1038/s41586-020-2649-2](https://doi.org/10.1038/s41586-020-2649-2)
- Hatch, N. A., Crawford, C. S., & Fabian, A. C. 2007, *MNRAS*, 380, 33, doi: [10.1111/j.1365-2966.2007.12009.x](https://doi.org/10.1111/j.1365-2966.2007.12009.x)
- Heckman, T. M. 1981, *ApJL*, 250, L59, doi: [10.1086/183674](https://doi.org/10.1086/183674)
- Heckman, T. M., Baum, S. A., van Breugel, W. J. M., & McCarthy, P. 1989, *ApJ*, 338, 48, doi: [10.1086/167181](https://doi.org/10.1086/167181)
- Hogan, M. T., McNamara, B. R., Pulido, F., et al. 2017a, *ApJ*, 837, 51, doi: [10.3847/1538-4357/aa5f56](https://doi.org/10.3847/1538-4357/aa5f56)
- Hogan, M. T., McNamara, B. R., Pulido, F. A., et al. 2017b, *ApJ*, 851, 66, doi: [10.3847/1538-4357/aa9af3](https://doi.org/10.3847/1538-4357/aa9af3)
- Hu, E. M., Cowie, L. L., & Wang, Z. 1985, *ApJS*, 59, 447, doi: [10.1086/191081](https://doi.org/10.1086/191081)
- Hunter, J. D. 2007, *Computing in Science and Engineering*, 9, 90, doi: [10.1109/MCSE.2007.55](https://doi.org/10.1109/MCSE.2007.55)
- Kirkpatrick, C. C., McNamara, B. R., & Cavagnolo, K. W. 2011, *ApJL*, 731, L23, doi: [10.1088/2041-8205/731/2/L23](https://doi.org/10.1088/2041-8205/731/2/L23)
- Lazareff, B., Castets, A., Kim, D. W., & Jura, M. 1989, *ApJL*, 336, L13, doi: [10.1086/185350](https://doi.org/10.1086/185350)
- Li, Y., Bryan, G. L., Ruszkowski, M., et al. 2015, *ApJ*, 811, 73, doi: [10.1088/0004-637X/811/2/73](https://doi.org/10.1088/0004-637X/811/2/73)
- Lim, P. L. 2020, *synphot*, 1.0.1, Zenodo, doi: [10.5281/zenodo.3971036](https://doi.org/10.5281/zenodo.3971036)
- Loubser, S. I., Sánchez-Blázquez, P., Sansom, A. E., & Soechting, I. K. 2009, *MNRAS*, 398, 133, doi: [10.1111/j.1365-2966.2009.15171.x](https://doi.org/10.1111/j.1365-2966.2009.15171.x)
- Maiolino, R., Russell, H. R., Fabian, A. C., et al. 2017, *Nature*, 544, 202, doi: [10.1038/nature21677](https://doi.org/10.1038/nature21677)
- Markwardt, C. B. 2009, in *Astronomical Society of the Pacific Conference Series*, Vol. 411, *Astronomical Data Analysis Software and Systems XVIII*, ed. D. A. Bohlender, D. Durand, & P. Dowler, 251. <https://arxiv.org/abs/0902.2850>
- Martis, N. S., Marchesini, D., Brammer, G. B., et al. 2016, *ApJL*, 827, L25, doi: [10.3847/2041-8205/827/2/L25](https://doi.org/10.3847/2041-8205/827/2/L25)
- McDonald, M., Veilleux, S., & Mushotzky, R. 2011a, *ApJ*, 731, 33, doi: [10.1088/0004-637X/731/1/33](https://doi.org/10.1088/0004-637X/731/1/33)
- McDonald, M., Veilleux, S., Rupke, D. S. N., & Mushotzky, R. 2010, *ApJ*, 721, 1262, doi: [10.1088/0004-637X/721/2/1262](https://doi.org/10.1088/0004-637X/721/2/1262)
- McDonald, M., Veilleux, S., Rupke, D. S. N., Mushotzky, R., & Reynolds, C. 2011b, *ApJ*, 734, 95, doi: [10.1088/0004-637X/734/2/95](https://doi.org/10.1088/0004-637X/734/2/95)
- McDonald, M., Bayliss, M., Benson, B. A., et al. 2012, *Nature*, 488, 349, doi: [10.1038/nature11379](https://doi.org/10.1038/nature11379)
- McDonald, M., McNamara, B. R., Voit, G. M., et al. 2019, *ApJ*, 885, 63, doi: [10.3847/1538-4357/ab464c](https://doi.org/10.3847/1538-4357/ab464c)
- McNamara, B. R., & Nulsen, P. E. J. 2007, *ARA&A*, 45, 117, doi: [10.1146/annurev.astro.45.051806.110625](https://doi.org/10.1146/annurev.astro.45.051806.110625)
- . 2012, *New Journal of Physics*, 14, 055023, doi: [10.1088/1367-2630/14/5/055023](https://doi.org/10.1088/1367-2630/14/5/055023)
- McNamara, B. R., & O’Connell, R. W. 1989, *AJ*, 98, 2018, doi: [10.1086/115275](https://doi.org/10.1086/115275)
- McNamara, B. R., Russell, H. R., Nulsen, P. E. J., et al. 2016, *ApJ*, 830, 79, doi: [10.3847/0004-637X/830/2/79](https://doi.org/10.3847/0004-637X/830/2/79)
- McNamara, B. R., Rafferty, D. A., Birzan, L., et al. 2006, *ApJ*, 648, 164, doi: [10.1086/505859](https://doi.org/10.1086/505859)
- McNamara, B. R., Russell, H. R., Nulsen, P. E. J., et al. 2014, *ApJ*, 785, 44, doi: [10.1088/0004-637X/785/1/44](https://doi.org/10.1088/0004-637X/785/1/44)
- Morrissey, P., Matuszewski, M., Martin, D. C., et al. 2018, *ApJ*, 864, 93, doi: [10.3847/1538-4357/aad597](https://doi.org/10.3847/1538-4357/aad597)
- O’Dea, C. P., Baum, S. A., Privon, G., et al. 2008, *ApJ*, 681, 1035, doi: [10.1086/588212](https://doi.org/10.1086/588212)
- Olivares, V., Salome, P., Combes, F., et al. 2019, *A&A*, 631, A22, doi: [10.1051/0004-6361/201935350](https://doi.org/10.1051/0004-6361/201935350)
- Peterson, J. R., & Fabian, A. C. 2006, *PhR*, 427, 1, doi: [10.1016/j.physrep.2005.12.007](https://doi.org/10.1016/j.physrep.2005.12.007)
- Pfrommer, C. 2008, *MNRAS*, 385, 1242, doi: [10.1111/j.1365-2966.2008.12957.x](https://doi.org/10.1111/j.1365-2966.2008.12957.x)
- Pipino, A., Kaviraj, S., Bildfell, C., et al. 2009, *MNRAS*, 395, 462, doi: [10.1111/j.1365-2966.2009.14534.x](https://doi.org/10.1111/j.1365-2966.2009.14534.x)
- Pope, E. C. D., Babul, A., Pavlovski, G., Bower, R. G., & Dotter, A. 2010, *MNRAS*, 406, 2023, doi: [10.1111/j.1365-2966.2010.16816.x](https://doi.org/10.1111/j.1365-2966.2010.16816.x)
- Predehl, P., & Schmitt, J. H. M. M. 1995, *A&A*, 293, 889
- Pulido, F. A., McNamara, B. R., Edge, A. C., et al. 2018, *ApJ*, 853, 177, doi: [10.3847/1538-4357/aaa54b](https://doi.org/10.3847/1538-4357/aaa54b)
- Rafferty, D. A., McNamara, B. R., Nulsen, P. E. J., & Wise, M. W. 2006, *ApJ*, 652, 216, doi: [10.1086/507672](https://doi.org/10.1086/507672)
- Revaz, Y., Combes, F., & Salomé, P. 2008, *A&A*, 477, L33, doi: [10.1051/0004-6361:20078915](https://doi.org/10.1051/0004-6361:20078915)
- Rupke, D. S. N. 2014a, *IFSRED: Data Reduction for Integral Field Spectrographs*, *Astrophysics Source Code Library*, record ascl:1409.004. <http://ascl.net/1409.004>
- . 2014b, *IFSFIT: Spectral Fitting for Integral Field Spectrographs*, *Astrophysics Source Code Library*, record ascl:1409.005. <http://ascl.net/1409.005>
- Rupke, D. S. N., Gültekin, K., & Veilleux, S. 2017, *ApJ*, 850, 40, doi: [10.3847/1538-4357/aa94d1](https://doi.org/10.3847/1538-4357/aa94d1)
- Russell, H. R., McNamara, B. R., Fabian, A. C., et al. 2016, *MNRAS*, 458, 3134, doi: [10.1093/mnras/stw409](https://doi.org/10.1093/mnras/stw409)
- . 2019, *MNRAS*, 490, 3025, doi: [10.1093/mnras/stz2719](https://doi.org/10.1093/mnras/stz2719)

- Ruszkowski, M., Enßlin, T. A., Brüggén, M., Begelman, M. C., & Churazov, E. 2008, *MNRAS*, 383, 1359, doi: [10.1111/j.1365-2966.2007.12659.x](https://doi.org/10.1111/j.1365-2966.2007.12659.x)
- Salomé, P., & Combes, F. 2003, *A&A*, 412, 657, doi: [10.1051/0004-6361:20031438](https://doi.org/10.1051/0004-6361:20031438)
- Salomé, P., & Combes, F. 2004, in *SF2A-2004: Semaine de l'Astrophysique Française*, ed. F. Combes, D. Barret, T. Contini, F. Meynadier, & L. Pagani, 505
- Sanders, J. S., Fabian, A. C., Hlavacek-Larrondo, J., et al. 2014, *MNRAS*, 444, 1497, doi: [10.1093/mnras/stu1543](https://doi.org/10.1093/mnras/stu1543)
- Sarazin, C. L. 1986, *Reviews of Modern Physics*, 58, 1, doi: [10.1103/RevModPhys.58.1](https://doi.org/10.1103/RevModPhys.58.1)
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525, doi: [10.1086/305772](https://doi.org/10.1086/305772)
- Simionescu, A., Werner, N., Böhringer, H., et al. 2009, *A&A*, 493, 409, doi: [10.1051/0004-6361:200810225](https://doi.org/10.1051/0004-6361:200810225)
- van der Walt, S., Colbert, S. C., & Varoquaux, G. 2011, *Computing in Science and Engineering*, 13, 22, doi: [10.1109/MCSE.2011.37](https://doi.org/10.1109/MCSE.2011.37)
- Van Rossum, G., & Drake, F. L. 2009, *Python 3 Reference Manual* (Scotts Valley, CA: CreateSpace)
- Vantyghem, A. N., McNamara, B. R., Edge, A. C., et al. 2017, *ApJ*, 848, 101, doi: [10.3847/1538-4357/aa8fd0](https://doi.org/10.3847/1538-4357/aa8fd0)
- Vantyghem, A. N., McNamara, B. R., Russell, H. R., et al. 2019, *ApJ*, 870, 57, doi: [10.3847/1538-4357/aaf1b4](https://doi.org/10.3847/1538-4357/aaf1b4)
- Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, *Nature Methods*, 17, 261, doi: [10.1038/s41592-019-0686-2](https://doi.org/10.1038/s41592-019-0686-2)