Clumpy Star Formation and AGN Activity in the Dwarf–Dwarf Galaxy Merger Mrk 709

Erin Kimbro1, Amy E. Reines1, Mallory Molina1, Adam T. Deller2, and Daniel Stern3

1Extreme Physics, Montana State University, Bozeman, MT 59717, USA
2Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, VIC 3122, Australia
3Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Mail Stop 169-221, Pasadena, CA 91109, USA

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Abstract

Nearby, low-metallicity dwarf starburst galaxies hosting active galactic nuclei (AGNs) offer the best local analogs to study the early evolution of galaxies and their supermassive black holes (BHs). Here we present a detailed multiwavelength investigation of star formation and BH activity in the low-metallicity dwarf–dwarf galaxy merger Mrk 709. Using Hubble Space Telescope Hα and continuum imaging combined with Keck spectroscopy, we determine that the two dwarf galaxies are likely in the early stages of a merger (i.e., their first pass) and discover a spectacular ~10 kpc long string of young massive star clusters (t ~ 10 Myr; M* ~ 10^5 M⊙) between the galaxies triggered by the interaction. We find that the southern galaxy, Mrk 709 S, is undergoing a clumpy mode of star formation resembling that seen in high-redshift galaxies, with multiple young clusters/clumps having stellar masses between 10^7 and 10^8 M⊙. Furthermore, we present additional evidence for a low-luminosity AGN in Mrk 709 S (first identified by Reines et al., using radio and X-ray observations), including the detection of the coronal [Fe X] optical emission line. The work presented here provides a unique glimpse into processes key to hierarchical galaxy formation and BH growth in the early universe.

Unified Astronomy Thesaurus concepts: Star clusters (1567); Young massive clusters (2049); Active galactic nuclei (16); Galaxy mergers (608); Dwarf irregular galaxies (417); Dwarf galaxies (416); Interacting galaxies (802); Blue compact dwarf galaxies (165); Low-luminosity active galactic nuclei (2033)

1. Introduction

Dwarf galaxies form the largest subset of galaxies in the universe (e.g., Binggeli et al. 1988), and their mergers play a crucial role in hierarchical galaxy formation (e.g., Stierwalt et al. 2017). Dwarf–dwarf mergers trigger intense star formation, and lead to the formation of blue compact dwarfs (BCDs; Stierwalt et al. 2017; Paudel et al. 2018; Kado-Fong et al. 2020; Zhang et al. 2020) that have strongly starbursting spectra and physical sizes of ~1 kpc (Bekki 2008). These low-mass, low-metallicity BCDs can host super star clusters (SSCs; Johnson et al. 2000; Reines et al. 2008b), which have properties expected of the progenitors of globular clusters (e.g., O’Connell et al. 1994).

At least some dwarf galaxies with stellar masses comparable to the Magellanic Clouds (M* ~ 10^8–10^9 M⊙) are also known to host massive black holes (BHs) with M_BH ~ 10^4–10^6 M⊙ (see Reines & Comastri 2016; Mezcua 2017; Greene et al. 2020, and references therein). These relatively small BHs place our best observational constraints on the masses of the first BH seeds in the earlier universe. Star-forming dwarfs hosting massive BHs today are particularly interesting (albeit hard to find) since they are more akin to high-redshift galaxies and may help us understand the interplay between BH and galaxy growth at early times.

Mrk 709 is uniquely suited for studying both hierarchical galaxy formation and the formation and evolution of BHs. Mrk 709 has been classified as a BCD (Gil de Paz et al. 2003) with very low metallicity (12 + log(O/H) = 7.7, or 10% Z⊙; Masegosa et al. 1994), and Reines et al. (2014) find that Mrk 709 consists of a pair of compact dwarf galaxies that appear to be interacting with one another. Moreover, Reines et al. (2014) present observational evidence at radio and X-ray wavelengths for an active massive BH in Mrk 709 S, the southern galaxy in the pair. Mrk 709 S has intense, on-going star formation with a star formation rate that is an order of magnitude higher than the Large Magellanic Cloud (and is significantly more luminous than the LMC), yet the two dwarf galaxies have similar stellar masses with M* < 3 × 10^8 M⊙ (van der Marel et al. 2002; Whitney et al. 2008; Reines et al. 2014).

In this work, we use multiwavelength data to confirm the interaction of Mrk 709 N and Mrk 709 S, study star formation throughout the system, and further investigate the active galactic nucleus (AGN) in Mrk 709 S. We use high-resolution Hα and continuum imaging from the Hubble Space Telescope (HST), Keck optical spectroscopy, and very long baseline interferometry (VLBI) radio imaging with the National Radio Astronomy Observatory (NRAO) High Sensitivity Array (HSA). We also reanalyze the SDSS DR8 spectra of Mrk 709 S to search for the AGN coronal line [Fe X]λ 6374, to provide further evidence for BH activity. Figure 1 shows HST imaging of Mrk 709 and Table 1 gives basic properties of the two-component galaxies, Mrk 709 S and Mrk 709 N.

We describe the observations in Section 2 and discuss the Mrk 709 system in Section 3. The properties of the star-forming regions are presented in Section 4. We present and analyze the evidence for the low-luminosity AGN in Mrk 709 S in Section 5, and summarize our results and conclusions in Section 6. In this paper, we assume H0 = 73 km s ^ -1 Mpc ^ -1. Mrk 709 S has a redshift of z = 0.052 based on Sloan Digital Sky Survey (SDSS) spectroscopy (Reines et al. 2014), which corresponds to a distance d = 214 Mpc. At this distance, 1" corresponds to ~1 kpc.

2. Observations

We obtained multiwavelength imaging of Mrk 709 with the Wide Field Camera 3 (WFC3) aboard HST. The images were taken over two orbits on 2015 November 18–19 (Proposal ID 14047; PI Reines). The galaxy was observed in three filters: a broadband near-IR filter (IR/F110W), a medium-band optical filter (UVIS/F621M), and a narrowband Hα filter (UVIS/F680N). For
each filter, we obtained four dithered exposures to facilitate cosmic-ray rejection, avoid bad pixels, and improve the PSF sampling. We obtained the calibrated and drizzled images produced by the STScI data reduction pipeline. The near-IR image has a plate scale of 0.13 pixel$^{-1}$ and the optical/H$\alpha$ images have plate scales of 0.04 pixel$^{-1}$. Our observations are summarized in Table 2.

![Figure 1. HST/WFC3 three-color image of Mrk 709. Red shows H$\alpha$ emission (UVIS/F680N), green shows near-infrared continuum (IR/F110W), and blue shows optical continuum (UVIS/F621M). The Keck/LRIS 1.70-wide long slit was positioned to cover both the northern and western galaxies, and the redshift of the latter indicated it is a background galaxy and not part of the Mrk 709 system. The star clusters in the bridge between Mrk 709 N and S are clearly seen in the WFC3 image.](image)

### Table 1

| Galaxy   | R.A.          | Decl.         | Redshift | $M_g$    | $g$       | $r$       | $i$       |
|----------|---------------|---------------|----------|----------|-----------|-----------|-----------|
| Mrk 709 S | 9:49:18.02    | +16:52:44.2   | 0.052    | $2.5 \times 10^9$ | 16.69 ± 0.00 | 16.77 ± 0.00 | 16.48 ± 0.00 |
| Mrk 709 N | 9:49:18.10    | +16:52:49.5   | 0.052    | $1.1 \times 10^9$ | 17.12 ± 0.01 | 16.73 ± 0.01 | 16.38 ± 0.01 |

**Note.** The reported R.A., decl., and $g$, $r$, and $i$ photometric values are from the 16th Data Release (DR16) of the Sloan Digital Sky Survey (SDSS-IV; Blanton et al. 2017; Ahumada et al. 2020). The redshift of Mrk 709 N is measured in this work using Keck spectroscopy. The redshift of Mrk 709 S and the stellar masses are from Reines et al. (2014).

## 2.2. Keck Spectroscopy

We observed Mrk 709 for 600 s with the dual-beam Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck I 10 m telescope on UT 2018 March 18. Our instrument setup consisted of the 1″ width slit, the 5600 Å dichroic, the 600 $\ell$ mm$^{-1}$ blue grism with $\lambda_{\text{blaze}} = 4000$ Å, and the 400 $\ell$ mm$^{-1}$ red grating with $\lambda_{\text{blaze}} = 8500$ Å. This configuration covers the full optical window at a resolving power of $R \approx 1100$. We used standard data reduction techniques in IRAF and for flux calibration we used observations obtained on the same night with the same instrument configuration of the standard stars Hiltner600 and Wolf 1346 from Massey & Gronwall (1990). The spatial resolution is 1″/2, due to the seeing on the night of the observation.

### Table 2

| Filter   | Instrument | Description           | Exp. Time |
|----------|------------|-----------------------|-----------|
| F110W    | WFC3/IR    | Near IR; 1.15 $\mu$m  | 400 s     |
| F621M    | WFC3/UVIS  | Optical; 0.62 $\mu$m  | 1600 s    |
| F680N    | WFC3/UVIS  | redshifted H$\alpha$  | 2300 s    |
We positioned the slit at a position angle of PA = 56.5° to cover both the northern and western galaxies, to measure their redshifts, and determine if they are part of the same system as Mrk 709 S. The redshift of the southern galaxy, Mrk 709 S, is known to be z = 0.052 from SDSS spectroscopy (Reines et al. 2014). Figure 2 shows the reduced Keck/LRIS spectra using a 1″ extraction width. The spectra indicate that Mrk 709 N is at the same redshift as Mrk 709 S (z = 0.052), but the western galaxy is at a higher redshift (z = 0.364) and therefore not part of the Mrk 709 system.

2.3. Very Long Baseline Interferometry

We obtained VLBI observations of Mrk 709 S on 2015 February 14. We used the HSA, comprised of the Very Long Baseline Array (VLBA) antennas along with the Green Bank Telescope (GBT) and the phased Very Large Array (VLA). The project code is BR204. All VLBA antennas observed with the exception of Maunakea (MK) and St. Croix (SC); Pie Town (PT) and Hancock (HN) were unavailable for a portion of the observation. 2 × 128 MHz subbands, centered at 1440 and 1696 MHz, were sampled in dual polarization. The bright source 4C 39.25 was observed twice to calibrate the instrumental bandpass, while JVAS J0949+1752 was observed every 5 minutes as a phase reference. The total observation duration was 5 hr.

We made use of a pipeline implemented using the ParselTongue (Kettenis et al. 2006) python interface to AIPS (Greisen 2003), optimized for 1.5 GHz VLBI observations. This pipeline has previously been used for numerous VLBA astrometric observations of radio pulsars, and a detailed description is available in Deller et al. (2019). Briefly, it applies a priori amplitude calibration, followed by bandpass correction derived from 4C 39.25, and then fringe-fitting and amplitude self-calibration using JVAS J0949+1752.

After calibration, the data were imaged using difmap (Shepherd 1997). Natural weighting was used, resulting in a synthesized beam size of 7 × 23 mas. We produced a 1″ × 1″ image covering the entire region of Mrk 709 S, with an image rms (σ) of 4 μJy. No source was visible in the dirty image with a peak brightness above 4.5σ, and we set a 5σ upper limit to the peak brightness of any 1.5 GHz radio emission to be 20 μJy beam⁻¹.

3. The Mrk 709 System

Figure 1 shows the HST images of Mrk 709. Three galaxies are apparent in the field of view. The northern and southern galaxies, Mrk 709 N and Mrk 709 S, were identified by Reines et al. (2014) using SDSS imaging; however, only Mrk 709 S had an SDSS spectrum, which indicated a redshift of z = 0.052 (d ~ 214 Mpc). Our new long-slit Keck spectroscopy covers the northern and western galaxies and indicates redshifts of z = 0.052 and z = 0.384, respectively. Therefore, while Mrk 709 N and Mrk 709 S are part of the same system, the western component is a background galaxy (J094917.85+165247.1) and not part of the Mrk 709 system. We present some of the basic galaxy properties for both Mrk 709 N and Mrk 709 S in Table 1.

There is a striking bridge of star clusters between Mrk 709 N and Mrk 709 S, strongly emitting in Hα. The bridge is a characteristic tidal feature indicating that the two dwarf galaxies are undergoing a merger/interaction. The bridge is ~10″ long. At the distance of Mrk 709, this corresponds to a projected physical length of ~10 kpc.

We estimate the star formation rates (SFRs) of Mrk 709 S, Mrk 709 N, and the bridge using Hα fluxes determined from our HST images and the following relation from Kennicutt & Evans (2012):

\[ \log \text{SFR} \left( M_\odot \text{yr}^{-1} \right) = \log \text{L}_\alpha - 41.27, \]  

where \( \text{L}_\alpha \) is the luminosity of Hα in units of erg s⁻¹. The Hα flux is given by:

\[ F_\alpha = (f_{\text{F680N}} - f_{\text{cont}}) \Delta \lambda_{\text{F680N}}, \]  

where \( f_{\text{F680N}} \) is the flux density in the F680N image, \( f_{\text{cont}} \) is the continuum flux density at the wavelength of redshifted Hα, and \( \Delta \lambda_{\text{F680N}} \) is the width of the F680N filter. The continuum is found by interpolating between the F621M and F110W flux densities in log \( f_\lambda \) versus log \( \lambda \) space since a power law is a good approximation of a stellar population spectrum redward of ~4000 Å (Leitherer et al. 1999). Table 3 presents the measurements and aperture definitions.

We find SFRs of approximately 1, 0.2, and 0.5 \( M_\odot \text{yr}^{-1} \) for Mrk 709 S, Mrk 709 N, and the bridge, respectively. These values should be taken as lower limits since the measured Hα fluxes cannot be corrected for extinction with the data in hand. It is also possible that our continuum estimates are artificially high due to nebular emission contaminating the broadband filters (Reines et al. 2010). While the redshifted [N II]λλ6548, 6584 lines fall in the F680N filter along with Hα, the contribution to the total flux and SFR is expected to be minor (~15% based on the SDSS spectrum of Mrk 709 S). We do not apply a correction to the measured SFRs as we do not know the contamination from the [N II]λλ6548, 6584 lines for every galaxy component.

Our SFR for Mrk 709 S is somewhat less than the value of 3.9 \( M_\odot \text{yr}^{-1} \) found by Reines et al. (2014) using the SDSS spectrum, which was taken in a 3″ aperture centered on Mrk 709 S and corrected for extinction using the Balmer decrement (Hα/Hβ = 3.47; Reines et al. 2014). The value derived here is likely lower due to the combination of a smaller aperture, no extinction correction, and uncertainty in the underlying stellar continuum using photometric measurements. We also note that both Reines et al. (2014) and this work assume that the AGN in Mrk 709 S does not contribute significantly to the observed Hα...
emission since the line ratios suggest that star formation dominates. The derived SFRs are very high given the low stellar masses of only $M_* \sim 2.5 \times 10^9 M_\odot$ and $M_* \sim 1.1 \times 10^9 M_\odot$ for Mrk 709 S and Mrk 709 N, respectively (Reines et al. 2014). Mrk 709 S has an SFR at least as large as the Milky Way.

4. Star-forming Regions

With the dramatically improved spatial resolution afforded by HST (e.g., compared to the SDSS images presented in Reines et al. 2014), we are now in a position to investigate individual star-forming regions and young star clusters within the Mrk 709 system. The H$\alpha$ and continuum images, along with population synthesis models, enable us to estimate the ages, ionizing luminosities, and stellar masses for each star-forming region/cluster.

4.1. Photometry of Star Clusters

We identify young star clusters in the narrowband H$\alpha$ (F680N) image. The regions are shown in Figure 3 and their coordinates are listed in Table 4. Using the astropy and photutils packages in Python, we perform aperture photometry on a total of 26 clusters: 6 in Mrk 709 S, 5 in Mrk 709 N, and 15 in the bridge between the two dwarf galaxies. We used circular apertures of radius 0''2. The background was estimated within an annulus of inner radius 0''45 and outer radius 0''65 centered on each cluster. However, we made multiple measurements varying the background since this is the dominant source of uncertainty in our photometry. Aperture corrections were applied to our final background-subtracted flux densities using the encircled energy fractions for a 0''2 aperture: 0.839, 0.847, and 0.712 for the F680N, F621M, and F110W images, respectively. The final magnitudes are listed in Table 4 and given in the STMAG photometric system.

Table 3

| Component     | R.A.     | Decl.    | Aperture Size (arcsec × arcsec) | PA (deg) | H$\alpha$ Flux ($10^{-14}$ erg s$^{-1}$ cm$^{-2}$) | SFR ($M_\odot$ yr$^{-1}$) |
|---------------|---------|---------|-------------------------------|----------|---------------------------------|--------------------------|
| Mrk 709 S     | 9:49:18.03 | +16:52:44.2 | 1.5 × 1.0                    | 110      | 3.15 ± 0.03                    | 1.0                      |
| Mrk 709 N     | 9:49:18.11 | +16:52:49.5 | 1.5 × 1.5                    | 0        | 0.46 ± 0.02                    | 0.2                      |
| Bridge        | 9:49:18.06 | +16:52:46.7 | 6.5 × 0.75                   | 52       | 1.6 ± 0.04                     | 0.5                      |

Note. Star formation rates of the different components of the Mrk 709 system are derived from our HST imaging. We use elliptical apertures with the given semimajor and semiminor axes, and position angles (PA). These SFRs should be considered lower limits (see Section 3).

Figure 3. HST/F680N image of Mrk 709 showing the observed H$\alpha$ emission and continuum. Mrk 709 N, Mrk 709 S, and the bridge associated with Mrk 709 system are labeled. We overplot the 0''2 apertures used to perform photometry on the identified star clusters, where those in Mrk 709 N are shown in cyan, those in Mrk 709 S are shown in magenta, and those in the bridge are shown in green.

4.2. Physical Properties of the Clusters

Estimates of the physical properties of the star clusters come from comparing our measurements to Starburst99 (v5.1) population synthesis models (Leitherer et al. 1999). We use a simulation of an instantaneous burst of $10^5 M_\odot$ with a Kroupa initial mass function. We adopt the Geneva evolutionary tracks with high mass loss, a metallicity of $Z = 0.001$ and the Pauldrach/Hillier atmospheres. The model metallicity is similar to that of Mrk 709 ($\sim$10% solar; Masegosa et al. 1994).

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https://hst-docs.stsci.edu/wfc3dhb/chapter-9-wfc3-data-analysis/9-1-wfc3-data-analysis
We estimate the ages of star clusters by comparing the equivalent width of Hα emission to the model predictions as a function of age. The equivalent width of Hα is given by the ratio of the flux of the Hα emission line (which is proportional to the ionizing flux from short-lived massive stars) to the continuum flux density at the same wavelength:

\[ W_{\text{H}\alpha} = \frac{F_{\text{H}\alpha}}{F_{\text{cont}}} \]  

(3)

This ratio is strongly dependent on age for stellar clusters between \(~3\) and \(20\) Myr old. The insensitivity before \(\lesssim 3\) Myr occurs because the most massive stars have not yet died, thereby reducing the ionizing flux, and the insensitivity after \(\sim 20\) Myr occurs because clusters older than this are not strong Hα emitters. The Hα flux is given by Equation (2) and determined for individual clusters using the same procedure as described in Section 3.

In Figure 4 we show the measured Hα equivalent width of star clusters in the Mrk 709 system as well as the model predictions as a function of age. The southern galaxy has the oldest star clusters, with an average age of \(13.3\) Myr. Star clusters in the northern galaxy have an average age of \(10.4\) Myr, and the star clusters in the bridge have an average age of \(7.5\) Myr. The star clusters in the bridge have the largest equivalent widths and are the youngest in the system.

We consider the derived ages to be upper limits for a couple of reasons. First, as described in Section 3, the continuum may be overestimated causing the Hα equivalent width to be underestimated. Second, the model metallicity is a factor of 2 lower than the measured value for Mrk 709. Given the known age–metallicity degeneracy, this may lead to an overestimate of the ages of the star clusters. To illustrate this, we show an additional model with \(Z = 0.004\) in Figure 4.

### 4.2.2. Ionizing Luminosities

We estimate the production rate of ionizing photons \(Q_{\text{LyC}}\) from the star-forming regions using the following equation derived from Condon (1992) for a \(10^4\) K gas:

\[ \left( \frac{Q_{\text{LyC}}}{s^{-1}} \right) \gtrsim 7.87 \times 10^{41} \left( \frac{L_{\text{H}\alpha}}{\text{erg s}^{-1}} \right) \]  

(4)

This only provides a lower limit on the ionizing luminosity since some photons may be absorbed by dust or escape the region before ionizing hydrogen atoms.

Adopting a distance of \(214\) Mpc, we find that the ionizing luminosities are in the range of \(3 \times 10^{49} \text{ to } 1.4 \times 10^{52} \text{ s}^{-1}\). Assuming a “typical” O-type star (type O7.5 V) produces \(Q_{\text{LyC}} = 10^{49} \text{ s}^{-1}\) (Vacca et al. 1996), \(~30\) to \(1400\) equivalent O stars are necessary to power the ionizing luminosities of the star clusters in Mrk 709.
which is comparable to young massive star clusters in other dwarf starburst galaxies (e.g., Reines et al. 2008a, 2008b).

4.2.3. Stellar Masses

We estimate the stellar masses of young star clusters using the ionizing luminosities and ages derived above. The models predict the number of Lyman continuum photons as a function of age given an input total stellar mass \( M_\star = 10^5 M_\odot \) in the model used here. Assuming stellar-mass scales linearly with the Lyman continuum photon production, we use the model prediction of \( \dot{Q}_{\text{LyC}} \) at the age of a cluster and multiply the input model mass by the ratio of the observed to the model ionizing luminosity. The stellar masses estimated using this method are in the range of \( M_\star \sim 10^5 - 10^6 M_\odot \) (see Table 5 and Figure 5).

The star clusters in Mrk 709 S are extremely massive with an average mass of \( M_\star \sim 4 \times 10^5 M_\odot \). This is significantly larger than young massive star clusters in the local universe (typically \( \lesssim 10^5 M_\odot \); Reines et al. 2008b; Whitmore et al. 2010) and the star formation in Mrk 709 S is more akin to that seen in higher redshift irregular galaxies (i.e., clump cluster and chain galaxies; Elmegreen et al. 2009). Both the clusters in Mrk 709 S and the clumps in these higher redshift galaxies have typical masses of \( 10^5 - 10^6 M_\odot \) and each contain an average of \( \sim 2 \% \) their galaxy mass. The total mass in clumps relative to total galaxy mass is also similar at \( \sim 10 \% \). The size scales are slightly different, however, with star-forming regions in clump clusters and chain galaxies having typical sizes of \( \sim 1.8 \) kpc (Elmegreen & Elmegreen 2005). This is comparable to the size of the brightest central region in Mrk 709 S containing \( \sim 5 \) massive clusters.

The star clusters in Mrk 709 N and the bridge are also massive, but not as extreme as in Mrk 709 S. The average masses are \( \sim 3 \times 10^6 M_\odot \) and \( \sim 7 \times 10^5 M_\odot \), for Mrk 709 N and the bridge, respectively, which are comparable to massive globular clusters. The total cluster mass in Mrk 709 N is \( M_\star \sim 1.7 \times 10^7 M_\odot \), roughly \( 2 \% \) of the total galaxy mass (\( M_\star \sim 1.1 \times 10^9 M_\odot \); Reines et al. 2014).

5. The Massive Black Hole in Mrk 709 S

Reines et al. (2014) identified a candidate massive BH in Mrk 709 S based on high-resolution radio and X-ray observations from the VLA and Chandra, respectively. They find a compact (\( \lesssim 0.3 \) arcsec) radio source with a 5 GHz luminosity of \( \nu L_\nu = (1.6 \pm 0.6) \times 10^{27} \text{ erg s}^{-1} \) that is consistent with the position of a hard X-ray point source with \( L_{2-10 \text{ keV}} \gtrsim (5.0 \pm 2.9) \times 10^{39} \text{ erg s}^{-1} \). The offset between the radio and X-ray sources is 0.017”, which is within the astrometric uncertainties. Assuming the radio and X-ray emission are indeed coming from the same source, Reines et al. (2014) argue for a BH origin and estimate a mass in the range of \( M_{\text{BH}} \sim 10^5 - 10^7 M_\odot \) using the fundamental plane of BH activity (e.g., Merloni et al. 2003; Falcke et al. 2004; Plotkin et al. 2012; Gültekin et al. 2019). A stellar-mass X-ray binary is firmly ruled out by the high radio luminosity.

5.1. A Radio-detected Low-luminosity AGN

Given that we cannot definitively say whether or not the radio and X-ray emission are indeed coming from the same physical source, we also consider separate origins for the radio and X-ray sources guided by our new HST imaging. Figure 6 shows that the X-ray source has a position consistent with multiple star clusters in Mrk 709 S, and could possibly be an exceptionally luminous high-mass X-ray binary (Lehmer et al. 2019) provided the radio emission is not associated with the X-ray source. From Figure 6, we also see that radio source 2 is spatially coincident with star cluster 4s (see Tables 4 and 5). We therefore investigate whether the radio emission could plausibly come from a thermal H II region or have a supernova (SNe) origin following Reines et al. (2020).

Under the assumption that radio source 2 is an H II region associated with star cluster 4s, we can calculate the expected H\alpha flux and compare this value to the measured value of \( F_{\text{H} \alpha} = \)
image is shown in color with the stretch adjusted so that individual star clusters are visible. We also show radio contours (magenta) and the position of the X-ray point source (and positional uncertainty; cyan) from the VLA and Chandra observations presented in Reines et al. (2014). Reines et al. (2014) associated a candidate massive BH with VLA radio source 2 as well as the X-ray source. The new HST observations presented here indicate that star cluster 4s is spatially coincident with VLA source 2, and consistent with the position of the X-ray source.

Figure 6. Close-up multiwavelength view of Mrk 709 S. The HST F680N image is shown in color with the stretch adjusted so that individual star clusters are visible. We also show radio contours (magenta) and the position of the X-ray point source (and positional uncertainty; cyan) from the VLA and Chandra observations presented in Reines et al. (2014). Reines et al. (2014) associated a candidate massive BH with VLA radio source 2 as well as the X-ray source. The new HST observations presented here indicate that star cluster 4s is spatially coincident with VLA source 2, and consistent with the position of the X-ray source.

1.43 × 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ (Table 5). Taking the 7.4-GHz flux density of 40 $\mu$Jy given by Reines et al. (2014) and using Equations (3) and 4(a) in Condon (1992) with an electron temperature of $T_e = 10^4 \text{ K}$, we expect an H$\alpha$ flux of $F_{H\alpha} = 3.91 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$ (modulo extinction) if the radio emission is thermal. This is a factor of 27$^*$ higher than the measured H$\alpha$ flux, which is exceptionally large even accounting for extinction due to dust. Reines et al. (2008a, 2008b) find that this factor is $\lesssim 3$ in their studies of thermal radio emission associated with young, optically visible star clusters in dwarf starburst galaxies. We therefore conclude that radio source 2 is dominated by nonthermal emission. This is consistent with the radio spectrum of source 2 (Reines et al. 2014), which shows flux density decreasing with frequency.

Next we show that the nonthermal radio emission from source 2 is unlikely to come from supernova remnants (SNRs) or younger SNe. Using the relation given by Chomiuk & Wilcots (2009) between the luminosity density of the brightest SNR/SNe in a galaxy and the SFR of the galaxy (and adopting the larger SFR of 3.9 $M_{\odot}$ yr$^{-1}$ from Reines et al. 2014), we expect the most luminous SNR/SNe in Mrk 709 S to have $L_{1.4 \text{ GHz}} \sim 3.6 \times 10^{20} \text{W Hz}^{-1}$. The spectral luminosity at 1.4 GHz of radio source 2 is estimated by Reines et al. (2014) to be $L_{1.4 \text{ GHz}} \sim 7 \times 10^{20} \text{W Hz}^{-1}$ assuming a spectral

### Table 5: Physical Properties of Star Clusters in Mrk 709

| Source | H$\alpha$ Flux ($10^{-16}$ erg s$^{-1}$ cm$^{-2}$) | H$\alpha$ EW (Å) | Age (Myr) | log $M_*$ ($M_{\odot}$) | $Q_{H\alpha}$ ($10^{20}$ s$^{-1}$) |
|--------|------------------|-----------------|-----------|-------------------------|--------------------------|
| **Mrk 709 S** | | | | | |
| 1s | 2.1(0.3) | 20(10) | (0.5)14(1.0) | 6.9(0.3) | 90(10) |
| 2s | 9.0(1.2) | 20(10) | (0.5)14(0.5) | 7.7(0.2) | 390(50) |
| 3s | 13.9(1.8) | 30(10) | (0.5)13(0.5) | 7.6(0.3) | 600(80) |
| 4s | 14.3(1.4) | 30(10) | (0.3)13(0.4) | 7.6(0.2) | 620(60) |
| 5s | 21.1(1.4) | 30(10) | (0.2)13(0.2) | 7.9(0.1) | 910(60) |
| 6s | 31.9(0.8) | 130(10) | (0.1)10(2.0) | 7.3(0.1) | 1380(40) |
| **Mrk 709 N** | | | | | |
| 1n | 1.1(0.1) | 100(50) | (0.8)10(1.5) | 6.0(0.6) | 50(10) |
| 2n | 1.5(0.3) | 100(50) | (0.9)11(2.1) | 6.2(0.7) | 70(10) |
| 3n | 10.9(0.6) | 110(20) | (0.3)10(0.4) | 6.9(0.2) | 470(30) |
| 4n | 9.1(0.5) | 130(20) | (0.4)10(2.0) | 6.8(0.2) | 390(20) |
| 5n | 0.7(0.1) | 150(110) | (1.1)9(2.9) | 5.6(0.9) | 30(10) |
| **Bridge** | | | | | |
| 1b | 1.9(0.1) | 200(20) | (0.1)9(2.0) | 5.8(0.1) | 80(10) |
| 2b | 2.1(0.1) | 210(20) | (0.9)10(2.1) | 5.8(0.1) | 90(10) |
| 3b | 3.7(0.1) | 590(50) | (0.2)5(0.1) | 5.1(0.2) | 160(10) |
| 4b | 3.2(0.1) | 380(20) | (0.1)7(0.2) | 5.7(0.1) | 140(10) |
| 5b | 1.1(0.1) | 260(20) | (0.1)8(0.2) | 5.5(0.1) | 50(10) |
| 6b | 8.0(0.1) | 420(20) | (0.2)7(0.2) | 6.0(0.1) | 350(10) |
| 7b | 3.8(0.1) | 270(130) | (1.0)8(1.3) | 6.0(1.3) | 160(10) |
| 8b | 12.0(0.1) | 300(10) | (0.1)8(0.1) | 6.4(0.1) | 520(10) |
| 9b | 1.5(0.1) | 340(10) | (0.1)8(0.1) | 5.5(0.1) | 70(10) |
| 10b | 2.6(0.1) | 530(30) | (0.5)10(0.5) | 5.0(0.1) | 110(10) |
| 11b | 7.1(0.1) | 320(10) | (0.1)8(0.1) | 6.1(0.1) | 310(10) |
| 12b | 2.4(0.1) | 1360(400) | (0.2)3(0.6) | 4.5(0.3) | 100(10) |
| 13b | 2.0(0.1) | 150(40) | (0.5)9(0.5) | 6.0(0.3) | 80(10) |
| 14b | 1.6(0.1) | 660(150) | (0.7)4(0.5) | 4.6(0.5) | 70(10) |
| 15b | 4.7(0.1) | 340(20) | (0.3)8(2.0) | 6.9(0.1) | 200(10) |

Note. All uncertainties in this table are shown in parentheses. The H$\alpha$ fluxes and EWs are measured from the HST imaging and are not corrected for extinction. The errors on the stellar masses do not include a systematic uncertainty of $\sim 0.3$ dex due to uncertainties in stellar evolution (Conroy et al. 2009).
index of $\alpha = -0.7 \ (S_{\nu} \propto \nu^\alpha)$. Given that this value is approximately $\sim 19 \times$ higher than the expected luminosity of the brightest SNR/SNe, it is highly unlikely that even multiple SNRs/SNe in cluster 4s could account for the radio emission. We therefore conclude that the most plausible explanation for the origin of radio source 2 is a massive BH.

This interpretation would have been further supported by the discovery of milliarcsecond-scale radio emission from source 2, which would have provided direct evidence of high brightness-temperature emission. However, the nondetection in our VLBI HSA observations (see Section 2.3) is still compatible with a massive BH. The angular resolution of the HSA observations is almost two orders of magnitude finer than that of the VLA observations, but the sensitivities are only comparable (4 $\mu$Jy beam$^{-1}$ versus 5.2 $\mu$Jy beam$^{-1}$). If source 2 is partially resolved into a core-jet object on milliarcsecond scales (which, given the VLA radio morphology, appears likely) the peak brightness could fall well below our HSA point-source detection limit of $\sim 20 \mu$Jy (5$\sigma$) at 1.4 GHz. The partial resolution of AGN emission in this way is commonplace: Deller & Middelberg (2014) performed a VLBI survey of $\sim 25,000$ mJy radio sources (which should be dominated by radio AGN) detected in the VLA FIRST survey (Becker et al. 1995) and found that only 30%–40% exhibited a milliarcsecond-scale core with a peak brightness $\geq 32\%$ of the arcsecond-scale flux density.

Figure 6 shows that VLA source 2 is surrounded by additional radio emission in Mrk 709 S. The radio morphology is suggestive of lobes/outflow from the central AGN and the radio luminosity supports this scenario. We find that the measured radio luminosity is more than an order of magnitude larger than that expected from the combination of both thermal emission from H II regions and a population of SNRs/SNe in Mrk 709 S. Based on the H$\alpha$ flux ($F_{\text{H}\alpha} = 3.15 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$) of Mrk 709 S measured in the same elliptical aperture ($1.5'' \times 1.5''$, PA = 110$^\circ$) as the radio emission, we expect the contribution from thermal radio emission to be $L_{5\text{GHz}} = 1.8 \times 10^{20}$ W Hz$^{-1}$ (Condon 1992). Following Reines et al. (2020) and using the results of Chomiak & Wilcots (2009), we expect a population of SNRs/SNe to contribute a cumulative spectral luminosity of $L_{5\text{GHz}} = 1.4 \times 10^{20}$ W Hz$^{-1}$. The sum of these values ($L_{5\text{GHz}} = 3.2 \times 10^{20}$ W Hz$^{-1}$) is only 8% of the measured radio luminosity ($L_{5\text{GHz}} = 3.9 \times 10^{20}$ W Hz$^{-1}$), strongly suggesting the radio emission is dominated by something other than H II regions and a population of SNRs/SNe. We therefore favor an AGN origin for the radio emission in Mrk 709 S.

If the X-ray source detected by Reines et al. (2014) is indeed associated with the massive BH (i.e., radio source 2), the X-ray luminosity would suggest the BH is radiating significantly below its Eddington luminosity. For a BH mass of $10^5 M_\odot$, and an X-ray to bolometric correction of $\sim 10$ (Vasudevan & Fabian 2009), the Eddington ratio would be $\sim 0.04$ (and even less for a more massive BH). A sub-Eddington BH such as this is expected to have a radiatively inefficient accretion flow (RIAF) and to be jet-dominated (e.g., Falcke et al. 2004), which is consistent with the observed radio emission. The optical line emission from such a weakly accreting BH could also easily be swamped by star formation and account for the H II-region-like line ratios measured in the SDSS spectrum obtained in a 3$''$ aperture (Reines et al. 2014).

5 While the spectral index is not well constrained and could be in the range of steep to flat, it is not inverted (Reines et al. 2014).

5.2. Optical Evidence for an AGN—[Fe X] $\lambda 6374$

In addition to radio and X-ray evidence for an AGN, we also detect [Fe X] $\lambda 6374$ in the SDSS spectrum of Mrk 709 S. [Fe X] is a known AGN coronal line (Penston et al. 1984; Netzer 2013), and has a high-ionization potential of 262.1 eV (Oetken 1977). This coronal line can be photoionized by the hard AGN continuum (e.g., Nussbaumer & Osterbrock 1976; Korista & Ferland 1989; Oliva et al. 1994; Pier & Voit 1995), or more likely in Mrk 709 S, mechanically excited by out-flowing winds caused by radio jets (Wilson & Raymond 1999).

The fit to the [Fe X] emission line in the SDSS DR16 spectrum is shown in Figure 7. The line has a flux of $9 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$, and a signal-to-noise ratio S/N = 2.25. The peak of the [Fe X] line is $\approx 3.3\sigma$ above the surrounding continuum. While this is not a 3$\sigma$ flux detection, the line is detected at the correct wavelength and could be diluted from host-galaxy light in the 3$''$ SDSS aperture (Moran et al. 2002).

Despite the presence of [Fe X], all three standard narrow-line diagnostic diagrams (Kewley et al. 2006) indicate Mrk 709 S is powered by star formation. The lack of AGN-like line ratios can be explained by a combination of contamination from star formation in the host galaxy and the BH powered by an RIAF. For RIAFs with Eddington ratios of $\sim 10^{-2}$ and lower, the broad lines, and potentially narrow lines, can disappear from the observed spectrum (Trump et al. 2011). Additionally, the relatively stronger radio emission in RIAFs (Meléndez et al. 2008) can drive relatively stronger radiative shock waves within the galaxy, which is likely causing the observed [Fe X] emission. Therefore, the X-ray, radio, and optical emission are all best explained by an RIAF-driven active BH.

6. Summary and Discussion

We have presented a study of the low-metallicity dwarf–dwarf galaxy merger Mrk 709 with the goal of investigating star formation and AGN activity. Our new observations include HST H$\alpha$ and continuum imaging, Keck spectroscopy, and
VLBI with the High Sensitivity Array. Our main results are summarized below.

1. Our spectroscopy confirms that Mrk 709 S and Mrk 709 N are part of the same system and our HST imaging reveals a striking bridge of young massive star clusters between the two galaxies, indicating an interaction/merger.

2. We estimate ages, ionizing luminosities, and stellar masses for 26 Hα-selected (i.e., young) star clusters in the Mrk 709 system. The youngest star clusters are in the bridge between the two dwarf galaxies, with ages \( \lesssim 10 \text{ Myr} \). The clusters in the galaxies have ages of \( \sim 10-15 \text{ Myr} \). Nearly all of the clusters we detect have stellar masses greater than \( 10^7 M_\odot \), which is the typical mass of a globular cluster.

3. Mrk 709 S is undergoing a clumpy mode of star formation resembling that in high-redshift galaxies (see Section 4.2.3 here; also Elmegreen et al. 2009). The clumps have stellar masses in the range of \( M_* \sim (1-8) \times 10^4 M_\odot \), and ionizing luminosities equivalent to \( \sim 100-1400 \) O-type stars.

4. We present evidence confirming the presence of a massive BH in Mrk 709 S that was first identified by Reines et al. (2014) using VLA and Chandra observations. In particular, we demonstrate that the radio luminosity is much too high to be produced by thermal H II regions and/or SNe/SNRs but can easily be explained by an AGN. The radio morphology at VLA resolution is suggestive of a core-jet object, which is consistent with our HSA nondetection.

5. We also detect the AGN coronal [Fe X] \( \lambda 6374 \) emission line in the SDSS spectrum of Mrk 709 S, likely caused by shocks from the radio jets of the active BH. This result, in combination with the detected radio lobes, is consistent with a RIAF-powered low-luminosity AGN.

We have presented definitive evidence that Mrk 709 N and S are in the midst of an interaction, resulting in a spectacular bridge of young massive star clusters between the two dwarf galaxies that resembles the “beads on a string” mode of star formation (e.g., Elmegreen & Elmegreen 1983; Mullan et al. 2011; Tremblay et al. 2014). These clusters have high equivalent widths implying that they are extremely young (\( \lesssim 10 \text{ Myr} \)) and therefore must have formed in the bridge. Their birth can be attributed to the tidal forces from the interaction. Tidal features such as tails and bridges can result in a “pile-up” of material that leads to dense cloud regions where it is possible for massive star clusters to form (Bournaud 2010). There is also recent star formation in Mrk 709 N and S, likely due to an influx of new gas as the two components approach each other. Starbursts in merging galaxies most often occur at two points in the process of a merger: (1) when the galaxies make their first pass, and (2) at their final coalescence (Bournaud 2010). The existence of two distinct galaxies, as well as the tidal bridge, indicates that Mrk 709 is in the early stages of a dwarf–dwarf merger.

There is also compelling evidence for an accreting massive BH in Mrk 709 S. Moreover, the BH has a position consistent with a \( M_* \sim 4 \times 10^4 M_\odot \) compact clump of star formation with a derived age of \( \sim 13 \text{ Myr} \). While the spatial overlap could be a projection effect, this is in stark contrast to the massive BH in the dwarf starburst galaxy Henize 2–10 (Reines et al. 2011, 2016; Reines & Deller 2012), which has no visible counterpart in optical or near-IR HST imaging. However, there are several young massive star clusters in the vicinity of the BH in that galaxy with dynamical friction timescales \( \lesssim 200 \text{ Myr} \), suggesting Henize 2–10 may represent a rare snapshot of nuclear star cluster formation around a preexisting massive BH (Nguyen et al. 2014). It is interesting to consider these different cases given that theories for the formation of BH seeds include collision in compact star clusters (Loeb & Rasio 1994; Begelman et al. 2000; Lodato & Natarajan 2006; Choi et al. 2015) as well as direct collapse scenarios (Portegies Zwart et al. 2004; Devecchi & Volonteri 2009; Davies et al. 2011; Lupi et al. 2014; Stone et al. 2017).

Our findings demonstrate that Mrk 709, with a metallicity of only \( Z \sim 0.1 Z_\odot \), may well be our best local analog of high-redshift galaxies during the early stages of BH growth and globular cluster formation. Detailed multiwavelength studies of additional BH-hosting star-forming dwarf galaxies are necessary to gain a more complete picture of the early stages of galaxy and BH evolution.

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