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PROCEEDING

Jet-triggered star formation in young radio galaxies

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Abstract

Emission in the ultraviolet continuum is a salient signature of the hot, massive, and consequently short-lived, stellar population that traces recent or ongoing star formation. With the aim of mapping star forming regions and morphologically separating the generic star formation from that associated with the galaxy-scale jet activity, we obtained high-resolution ultraviolet (UV) imaging from the *Hubble Space Telescope* for a sample of nine compact radio sources. Out of these, seven are known Compact Steep Spectrum (CSS) galaxies that host young, kiloparsec-scale radio sources and hence are the best candidates for studying radio-mode feedback on galaxy scales, while the other two form a control sample of larger sources. Extended UV emission regions are observed in six of the seven CSS sources showing close spatial alignment with the radio-jet orientation. If other mechanisms possibly contributing to the observed UV emission are ruled out, this could be evidence in support of jet-triggered star formation in the CSS phase of radio galaxy evolution and in turn of the "positive feedback" paradigm of host–active galactic nuclei interaction.

KEYWORDS

active galactic nuclei, feedback, galaxies, star formation, young radio source

1 | INTRODUCTION

Compact Steep Spectrum (CSS) sources are a subclass of compact radio-luminous active galactic nuclei (AGN) characterized by projected linear sizes from ~ 500 parsecs (pc) to 20 kiloparsecs (kpc), and steep radio spectra

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($\alpha \geq 0.5$, where flux density, $S \propto \nu^{-\alpha}$) that tend to peak at radio frequencies below about ~400 MHz (O'Dea & Saikia 2021). Gigahertz-peaked spectrum sources and High-Frequency Peakers, collectively referred to as Peaked Spectrum (PS) sources, along with the Compact Symmetric Objects (CSOs) encompass the other types of compact radio sources that typically show projected linear sizes smaller than 500 pc.

While the small-scale extent of jet emission in compact sources could be attributed to episodic or transient activity (Kunert-Bajraszewska et al. 2010), confinement to host galaxy atmospheres (Wilkinson et al. 1984), or radio-enhancement in intrinsically weaker sources (Dicken et al. 2012; Gopal-Krishna & Wiita 1991; O'Dea 1998; Tadhunter et al. 2011) due to interactions with dense interstellar medium (ISM) of host galaxies, it has been argued that a section of this compact radio source population is likely to be intrinsically small, young radio sources (O'Dea & Saikia 2021) that would eventually grow and develop into large-scale radio galaxies and quasars (e.g., FR I/II galaxies; Fanaroff & Riley 1974) and thus represent an early stage of radio galaxy evolution (Fanti et al. 1995; O'Dea 1998; Readhead et al. 1996).

This period of infancy is where the radio source is likely to interact vigorously with the surrounding gas, driving shocks through the ISM, and triggering or boosting star formation in the host galaxy. Given the lifetimes of hot, massive stars, this so-called positive feedback would happen entirely during the CSS phase when the nuclear jets are confined to galaxy extents. Hence, jet-induced star formation is expected to be a key signature of radio-mode feedback on galaxy scales (Dugan et al. 2014; Fragile et al. 2017; Gaibler et al. 2012; Rees 1989).

The phenomenon of jet-driven star formation has been supported by observational evidence in some extended radio sources (Croft et al. 2006; Nesvadba et al. 2020; Salomé et al. 2015; Zovaro et al. 2020). The observation of similar effects in the context of young radio sources, however, has been limited. Since PS/CSO sources have sizes too small to be sufficiently resolved on the scale of the radio source in the optical, infrared, and ultraviolet (UV) bands with current facilities, CSS sources arguably provide the best opportunity to study the effects of galactic-scale jet activity on host ISM.

Extended emission-line regions in CSS galaxies have been often observed to be co-spatial and aligned with the radio source (Axon et al. 2000; Privon et al. 2008). Such an alignment effect is generally attributed to outflows driven by the kpc-scale radio source (see O'Dea & Saikia 2021 and the references therein). Therefore, the observation of extended UV emission with a similar close spatial alignment to radio source orientation in these compact sources is a justifiable argument in favor of the radio-jet feedback paradigm.

Following our pilot study that detected extended UV light aligned with the radio source in two out of three CSS sources (3C 303.1 and 1814–637; Labiano et al. 2008), we went on to conduct a UV imaging survey using the *Hubble Space Telescope* (HST) of a larger sample of nine sources. We also obtained short optical images which allow us to confirm that the UV light is indeed due to newly formed stars as well as to determine the spatial distribution of the older stellar population.

2 THE SAMPLE

The nine compact radio galaxies selected for our study (listed in Table 1) were chosen such that they are at relatively nearby redshifts ($z \lesssim 0.6$), thus eliminating strong effects due to evolution with cosmic time. Their radio source sizes range from $1''$ to $8''$ so as to have good resolution with the HST/*Wide Field Camera 3* (WFC3) imager along the radio source. These target sources were drawn from well-defined samples compiled in previous studies (Column 6, Table 1), seven of which are known CSS radio sources while the other two represent a control sample of larger sources.

3 OBSERVATIONS

We carried out high-resolution ($\sim 0.05''$/pix) imaging of the nine compact radio sources with the UVIS channel on the HST's WFC3 in the optical (6000 – 8500 Å) and ultraviolet (2000 – 3500 Å) bands. The filter selection (Table 1) was based on our requirement of imaging the UV and optical continua free of bright emission lines. In addition, archival radio maps of the target CSS sources from the *Very Large Array* (VLA) were used to determine the spatial relationship between the extended UV emission regions and the radio source.

The HST/WFC3 imaging data were reduced using a combination of basic calibrations performed as part of the standard HST *calwf3* pipeline—that is, bias and dark current subtraction, flat-fielding, linearity, and charge transfer efficiency corrections—with manual post-pipeline reprocessing using the Drizzlepac software package (Hoffmann et al. 2021) for improved cosmic-ray rejection, geometric distortion correction, and customization of image alignment and dithering to produce the final drizzled images.

TABLE 1 List of observed targets

Source	Catalog name	z	Radio size (arcsec)	Proj. linear size (kpc)	Sample[a]	FUV filter	V filter	UV detection[b]
B0258 + 35	NGC 1167	0.017	3.8	1.32	G05	F225W	F621M	
B1014 + 392[c]	4C 39.29	0.536	6.1	39.03	F01	F336W	F763M	
B1025 + 390	4C 39.32	0.361	3.2	16.28	F01	F336W	F763M	✓
B1037 + 30	4C 30.19	0.091	3.3	5.63	G05	F225W	F621M	✓
B1128 + 455		0.404	0.9	4.91	F01	F336W	F763M	✓
B1201 + 394		0.445	2.1	12.14	F01	F336W	F845M	✓
B1203 + 645	3C268.3	0.371	1.4	7.25	O98	F336W	F763M	✓
B1221-423	PKS 1221–42	0.171	1.5	4.40	B06	F275W	F689M	✓
B1445 + 410[c]		0.195	8.1	26.41	F01	F275W	F689M	

[a] Samples: G05 (Giroletti et al. 2005) = low power CSS; F01 (Fanti et al. 2001) = moderate power CSS; O98 (O'Dea 1998 = Stanghellini et al. (1997) + Fanti et al. (1990)); B06 (Burgess & Hunstead 2006) = southern 3C equivalent.
[b] The subset of target sources with a definite detection in the UV band is signified with ✓ marks.
[c] The non-CSS control sample (projected linear size of radio source >20 kpc).

4 | UV MORPHOLOGY AND JET-DRIVEN STAR FORMATION

Our aim was to study the spatial relationship between star formation and powerful radio-jet emission by morphologically separating the generic star formation due to gas in fall, from that associated with the kpc-scale radio sources and hence probably triggered due to jet activity.

With our near-UV band imaging, we detected extended UV continuum emission in six out of the nine compact radio sources in our sample (Figure 1). While the bright UV emission clustered around the core regions is more likely to be due to the central AGN, the extended and clumpy structures in the UV are more likely to be star-forming regions. A visual comparison of the UV and optical band images of the CSS host galaxies (Figures 1 and 2) shows the distribution of the younger stellar populations as evident from UV continuum emission, relative to the general galaxy morphology.

The extended UV light exhibits strong alignment with the radio-jet axes in at least five out of our target sources (a higher resolution radio image is needed to confirm the presence of this effect in B1201 + 394, see Figure 1), which suggests a dynamic feedback relationship between jet activity and the host galaxy ISM. This might be strong evidence in support of jet-induced star formation, if the clumpy/extended UV continuum emission observed in these CSS sources could indeed be attributed to star-forming regions.

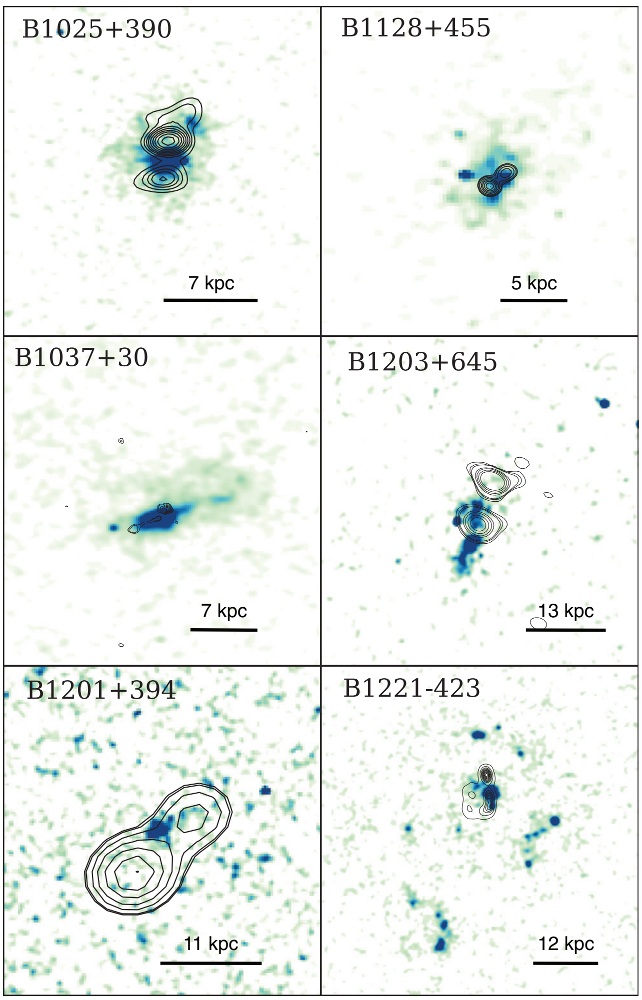

FIGURE 1 HST UV continuum images overlaid with contours from VLA radio data

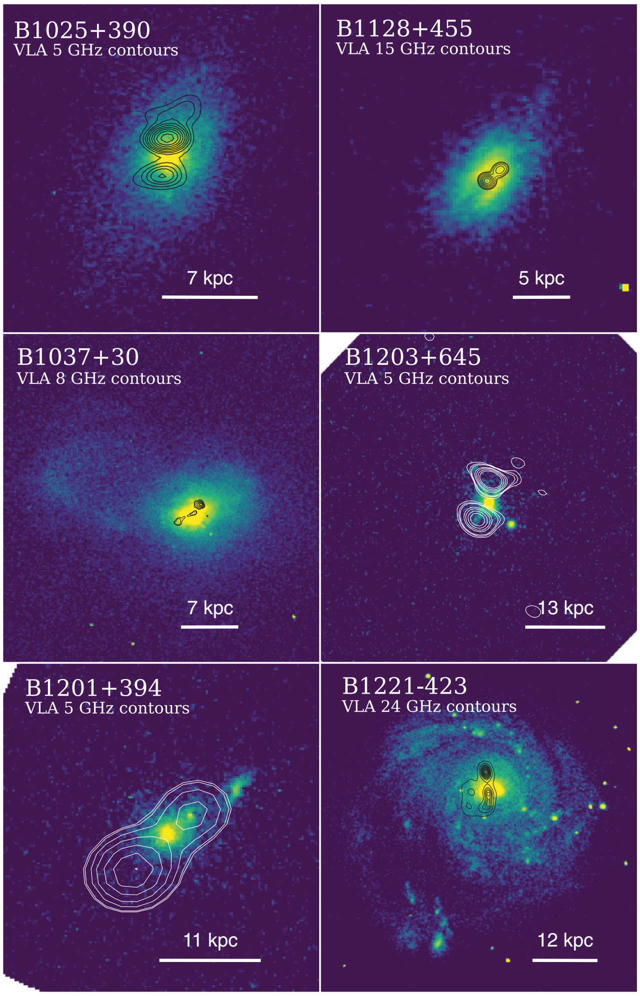

FIGURE 2 HST/WFC3 optical continuum images overlaid with VLA radio observations for the six UV-detected CSS targets

5 | DISCUSSION

While our data show strong evidence in support of jet-driven star formation during the CSS phase of radio evolution, further investigation is required to confirm the origin of the observed UV emission. While the extended UV-continuum emission co-spatial with the radio source is likely to have originated in star formation due to dense shocked gas in the galactic ISM, the UV light extending beyond the radio source could be a consequence of past merger events in some of the sources, as evident from their perturbed optical morphologies. Another possibility is a repetitive or restarted activity scenario where the UV emission on larger scales was caused by an older radio source, larger in extent than the present, nascent radio source. Additionally, there might be contamination from AGN-related components, that is, scattered UV light from the central AGN and/or nebular continuum emission from AGN-ionized emission regions (Cimatti et al. 1997; Dickson et al. 1995; Tadhunter et al. 2002; Wills et al. 2002). These, if present, would be apparent in polarimetric UV imaging and spectroscopic observations of the CSS galaxies, respectively. We plan to address these questions as part of our ongoing and future work.

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Chetna Duggal is a PhD student at the University of Manitoba. Her doctoral thesis is focused on studying the signatures of host–AGN interaction in powerful radio galaxies using a multi-wavelength approach.

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