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Feedback in the Extremely Violent Group Merger NGC 6338

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Abstract

The galaxy group NGC 6338 is one of the most violent group–merger systems known to date. While the central dominant galaxies rush at each other at 1400 km s\(^{-1}\) along the line of sight, with dramatic gas heating and shock fronts detected, the central gas in the BCGs remains cool. There are also indications of feedback from active galactic nuclei, and neither subcluster core has been disrupted. With our deep radio uGMRT data at 383 and 650 MHz, we clearly detect a set of large, old lobes in the southern BCG coinciding with the X-ray cavities, while the northern and smaller BCG appears slightly extended in the radio. The southern BCG also hosts a smaller set of lobes perpendicular to the larger lobes, but also coinciding with the inner X-ray cavities and matching the jet direction in the parsec-resolution VLBA image. Our spectral analysis confirms the history of two feedback cycles. The high radio frequency analysis classifies the compact source in the southern BCG with a power law, while ruling out a significant contribution from accretion. The radio lightcurve over three decades shows a change about 10 yr ago, which might be related to ongoing feedback in the core. The southern BCG in the NGC 6338 merger remains another prominent case where the direction of jet-mode feedback between two cycles changed dramatically.

Unified Astronomy Thesaurus concepts: Galaxy groups (597); Spectral energy distribution (2129); Active galactic nuclei (16); Radio continuum emission (1340)

1. Introduction

The standard ΛCDM cosmological model predicts collapsed structures growing from small density fluctuations through gravity. These collapsed overdensities can become the largest objects in the Universe through the infall and merger of surrounding matter. Consequently, galaxy clusters, the largest gravitationally bound structures, are undergoing mergers at multiple stages during their evolution. Galaxy cluster mergers are the most energetic events in the Universe (10\(^{53}\) erg s\(^{-1}\)), with expected merger velocities around 500–700 km s\(^{-1}\) based on cosmological simulations (Thompson & Nagamine 2012). Observations of mergers with much higher velocities (Markevitch et al. 2002) require a tail to this velocity distribution.

Galaxy clusters are filled with a hot, X-ray bright plasma (intracluster medium, ICM), with central cooling timescales often less than 1 Gyr, predicting large amounts of cold molecular gas in the centers of clusters that can fuel star formation (Fabian et al. 1984; Mark Voit & Donahue 2011; Stern et al. 2019). However, the observed amounts of cold gas and star formation largely are far below the high predictions. A solution began to appear after the discovery of powerful relativistic jets launched by the supermassive black holes (SMBHs) in the cluster-center galaxies heating the ICM (Churazov et al. 2001). It is now established that active galactic nuclei (AGNs, which harbor the SMBH) are part of the feedback mechanism that regulates the balance between infalling cold gas that has condensed from the ICM versus jets mechanically heating the environment (e.g., McNamara et al. 2000; Forman et al. 2007). The energy available from the jets can be estimated from X-ray measurements of the volume and pressure of the displaced ICM. Birzan et al. (2004), O’Sullivan et al. (2011), Panagoulia et al. (2014), and others have shown that the energy output is sufficient to prevent most of the ICM from cooling.

The released energy of a major merger can significantly disturb the feedback cycle that is established within a galaxy cluster or group, and can even disrupt cool cores. Observationally, the correlation between the cool core / non-cool core and merging states has been demonstrated (e.g., Chon et al. 2012; Lovisari et al. 2017). On the simulation side, several studies confirm the observed trend (e.g., ZuHone 2011; Valdarmini & Sarazin 2021) and point out that cool cores do not survive a major merger, due to the high-entropy gas brought into the core. Only off-axis mergers with smaller mass ratios tend to retain the cool-core properties. However, some other simulation studies do not find a clear trend of cool-core clusters being more relaxed (e.g., Barnes et al. 2018), and these indicate that events other than mergers can disrupt cool cores. More recently, Sharma et al. (2021) found that galaxy simulations of gas-rich major mergers do not enhance the AGN activity as one might expect due to the new supply of cold gas. Therefore, to understand the AGN feedback process fully, and how it might be triggered or interrupted through mergers, observations of merging systems with an ongoing feedback cycle are particularly interesting.
Despite most studies focusing on galaxy clusters, galaxy groups have turned out to be at least as important: They host most of the galaxies (Eke et al. 2006) and matter in the universe (Fukugita et al. 1998). Their hot intragroup medium (IGM) cools even faster than the ICM through X-ray line emission, while the gravitational potential is shallower, which requires strong and fine-tuned AGN feedback as a balance. Yet their dominant galaxies show little star formation (SF) and only limited cold gas content (McDonald et al. 2018; O’Sullivan et al. 2018; Schellenberger et al. 2020b; Kolokythas et al. 2022). The possibility has been proposed that gas has been driven out to large radii by the AGN, diminishing the efficiency of AGN reheating (e.g., Eckert et al. 2021). At the same time, star formation is also highly suppressed in the central dominant galaxies (CDGs) of groups with respect to CDGs of clusters.

The nearby galaxy group NGC741 shows many of these interesting features: Schellenberger et al. (2017) describe the narrow X-ray filaments around the old radio galaxy in the center of the group (also called NGC741), as well as in the vicinity of the infalling head-tail radio galaxy, NGC742, which has strongly bent jets and a radio tail extending more than 100 kpc in projection. The ongoing merger shows signs of disturbance in the group (sloshing, rings in the optical image of the infalling galaxy), but the cool core and the structure of the BCG seem to be largely unaffected.

A far more massive merger has been observed in the galaxy group NGC6338 (Dupke & Martins 2013; O’Sullivan et al. 2019; Wang et al. 2019). It appears to be a unique case of a highly violent group–group merger with velocities up to 1800 km s$^{-1}$, where dominant galaxies show signs of feedback. The balancing of the feedback cycle during an ongoing major merger is largely unknown and can be studied in detail in NGC6338. The hydrostatic mass from the X-rays is close to $10^{14} M_\odot$, and past studies have found that the merger interaction heats the gas up to 5 keV and creates shocks in the ICM. The merger is mostly along the line of sight, with the larger dominant galaxy located to the south. The two dominant galaxies are separated in projection by about 1′ (32 kpc). Pan et al. (2020) report Hα and CO detections in the northern core, which both appear slightly offset from the center of the galaxy. The cold and warm gas masses are consistent with cooling predictions, implying an offset cooling scenario in the northern BCG.

The southern BCG contains bright, colder X-ray gas with short cooling times, as well as Hα filaments that extend 17″ (8 kpc in projection) and are correlated with the X-ray structures, and it hosts an AGN that is visible in the radio band, which indicates ongoing feedback. Its stellar mass, $\log M_{*,\text{BCG}} = 11.47$ (Marino et al. 2016), is relatively high for a group merger constituent, with a rotation around the major photometric axis (Tsatsi et al. 2017). Star formation estimates from K-band measurements show a large value around $1 M_\odot$ yr$^{-1}$, but the presence of the AGN might lead to an overestimate (O’Dea et al. 2008). More detailed IR photometry (Crawford et al. 1999; Quillen et al. 2008) classifies the BCG as quiescent and indicates the presence of lines such as OIII.

We recently obtained deep uGMRT observations in two bands to answer the open question: Are there radio jets or radio lobes in one or both of the cores? These observations will help to understand the feedback history, and compare it to relaxed galaxy groups with strong feedback, such as NGC 5044, which is the X-ray brightest group in the sky. NGC 5044 shows strong signs of gas cooling throughout the wave band, such as cold X-ray and Hα filaments (David et al. 2017), [C II] and [N II] line emission and CO emission (David et al. 2014; Werner et al. 2014), and old radio plasma (O’Sullivan et al. 2013). Three distinct AGN cycles are imprinted in the hot X-ray bright gas, and a new feedback cycle of the AGN is just starting (Schellenberger et al. 2020a).

This paper is structured as follows. In Section 2, we describe the setup and data reduction of the recent uGMRT observations. Several other data sets have been included in this study, such as archival VLA and VLBA observations, as well as our recent Submillimeter Array (SMA$^3$) and IRAM observation at high frequencies, which are also described in Section 2. Our results, such as the description of past feedback cycles in the southern BCG and the current state of the AGN and connected jets, are presented in Section 3. Section 4 provides a discussion of the radio and submm results, including the age of past feedback cycles and opportunities for future X-ray missions. We summarize our findings in Section 5.

Throughout this paper, we assume a flat $\Lambda$CDM cosmology with the following parameters: $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = h \cdot 100$ km s$^{-1}$ Mpc$^{-1}$, with $h = 0.7$, which gives an angular scale of 0.528 kpc per arcsec at redshift 0.027 ($D_A = 109$ Mpc) of NGC 6338. Uncertainties are stated at the 68% confidence level, and cluster masses refer to a radius within which the mean density of the cluster is 500 times the critical density of the Universe at the cluster redshift.

2. Observations

The main goal of the dedicated uGMRT observations was to find signatures of feedback, which is ideal for this instrument, with its decent spatial resolution at low frequencies (below ~1 GHz). We decided to expand this by including higher-frequency data from the VLA and several other published values, to construct and fit an SED over three orders of magnitude in frequency, which reveals the emission mechanisms. At the high-frequency end, we included our recent SMA continuum observation at 230 GHz, to complete the SED. Repeated VLA observations indicate the radio variability of the central radio source in the southern BCG, and the IRAM 30 m CO measurements can quantify the reservoir of cold molecular gas.

2.1. uGMRT Data Reduction

The upgraded Giant Metrewave Radio telescope (uGMRT) is equipped with four wideband receivers. We observed NGC 6338 in bands 3 (300–500 MHz) and 4 (550–850 MHz) (see Table 1). Both observations were recorded with 5.37 s integration time, 4096 channels, and two Stokes parameters. The hardware-based removal of radio frequency interference (RFI)$^8$ was not enabled. For band 3, 27 of 30 antennas were available, while for the band 4 observation, only 26 antennas were operational. Each observation ends with a 10-minute scan of 3C48, which was used as a flux calibrator for both data sets (more details on the observations are given in Table 1). The reduction of uGMRT data utilized the SPAM pipeline.

$^7$ The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics, and is funded by the Smithsonian Institution and the Academia Sinica.

$^8$ http://www.ncra.tifr.res.in/ncra/gmrt/gmrt-users/online-ri-filtering
We reduced the archival VLA data before 2012 using the Astronomical Image Processing System (AIPS version 31DEC22; Greisen 1990, 2003) and the vlaproc module. We load the raw VLA files into AIPS and apply the flux scale to the corresponding flux calibrator observation with SETJY, including the options OPTYPE = CALC. The parameter APARM(2) is set in such a way as to match the time of the observation. We then determine the telescope-based calibration, set the flux and phase calibrator names, and determine the flux densities for the calibration sources from the primary calibrator. Finally, we apply the solutions to the target. Imaging of each observation has been done using tclean in CASA with Briggs robust weighting $r = 1$.

The EVLA/Jvla observations 12A182 and 15A215 have been reduced using the CASA VLA pipeline (version 5.6.3-19), followed by imaging of the target scans with tclean and applying several phase-only self-calibration cycles. Also, these observations should only provide a flux of the radio point source.

We note that the source flux in Table 2 refers to the flux of a point-like source, and therefore the r.m.s. value states the statistical uncertainty of the extracted fluxes. Additionally, we assume a 3% systematic uncertainty (Perley & Butler 2017). We note that observation AM701 was used to characterize the high-frequency radio spectrum, because all four bands ($C, X, K_u$, and $K$) are observed simultaneously (see Section 3.1.2). We did not combine or simultaneously image VLA observations.

### 2.3. SMA Data Reduction

We observed NGC 6338 at 230 GHz with the SMA to measure the current high-frequency flux (project 2021B-S068, PI Schellenberger). Seven of the total eight 6 m antennas were operational during the observations performed in the compact configuration on 2022 January 15 and 2022 January 17, with total observing times of 1 h 33 minutes and 2 hr 4 minutes, respectively. A reliable flux calibration was ensured through a scan of Ceres during each track. The time dependence of the complex gain was calibrated through frequent observations of 1740 + 521. The total on-target time sums to 139 minutes. Data reduction was performed using the IDL package MIR (Gurvell et al. 2007), and the important steps include the flagging of unusable visibilities, a system temperature calibration, and a baseline-based bandpass calibration using scans of 3C345 and 3C279 with the pass_cal task. Using the flux calibrator observation, we constrained the gain amplitude of the phase calibrator by applying sma_flux_cal and flux_measure for each sideband and receiver separately. For a combined imaging of both tracks in CASA, we apply the correct weights.
Table 2

<table>
<thead>
<tr>
<th>Project</th>
<th>Configuration</th>
<th>Date</th>
<th>Band</th>
<th>Time (min)</th>
<th>Calibrator</th>
<th>r.m.s. (mJy bm⁻¹)</th>
<th>Source Flux (mJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS452</td>
<td>CnB</td>
<td>Jan 1992</td>
<td>C</td>
<td>5.2</td>
<td>3C286/1658+476</td>
<td>0.4</td>
<td>30.9</td>
</tr>
<tr>
<td>AF233</td>
<td>A</td>
<td>Oct 1992</td>
<td>C</td>
<td>1.0</td>
<td>3C286/1638+573</td>
<td>0.59</td>
<td>31.4</td>
</tr>
<tr>
<td>3C308/NVSS</td>
<td>D</td>
<td>March 1995</td>
<td>L</td>
<td>0.5</td>
<td>3C286</td>
<td>0.45</td>
<td>57.5</td>
</tr>
<tr>
<td>AE110</td>
<td>C</td>
<td>June 1997</td>
<td>C</td>
<td>9.8</td>
<td>1635+381/1740+521</td>
<td>0.09</td>
<td>27.9</td>
</tr>
<tr>
<td>AB879/FIRST</td>
<td>B</td>
<td>July 1998</td>
<td>L</td>
<td>3.0</td>
<td>3C286</td>
<td>0.14</td>
<td>49.1</td>
</tr>
<tr>
<td>AM701</td>
<td>D</td>
<td>Dec 2001</td>
<td>C</td>
<td>1.0</td>
<td>3C286/1740+521</td>
<td>0.36</td>
<td>25.6</td>
</tr>
<tr>
<td>12A182</td>
<td>B</td>
<td>June 2012</td>
<td>C</td>
<td>14.4</td>
<td>3C286/Multiple</td>
<td>0.018</td>
<td>28.1</td>
</tr>
<tr>
<td>15A215</td>
<td>A</td>
<td>Aug 2015</td>
<td>C</td>
<td>40.6</td>
<td>3C286/1740+521</td>
<td>0.013</td>
<td>28.1</td>
</tr>
<tr>
<td>VLASS T25t13</td>
<td>B</td>
<td>Oct 2017</td>
<td>S</td>
<td>1.0</td>
<td>3C286+3C138</td>
<td>0.12</td>
<td>44.8</td>
</tr>
</tbody>
</table>


Scaling factors (MIRFITstoCASA.py). After two phase self-calibration steps without flagging bad solutions, we improved the noise slightly, yielding a final r.m.s. of 0.46 mJy bm⁻¹ and a beam size of 6′′1×2′′7. The measured flux at 225 GHz of the central point source with the SMA is 3.9±0.5 mJy.

2.4. VLBA Data Reduction

To better understand the current state of the southern BCG in NGC 6338, we analyzed the archival VLBA observation (Project BE063/F, PI A. Edge) in C band taken in 2013 May. The scan of NGC 6338 has data taken from nine antennas (SC missing) and a spectral setup of eight spectral windows, with each window having a 32 MHz bandwidth.

We used the VLBARUN task in AIPS to perform the VLBA calibration, using the scan of 3C345 as fringe finder and bandpass calibrator and J1722+5856 for phase referencing. The solution interval was set to 10 minutes, and the selected reference antenna is Pie Town (PT). After exporting the 19-minute calibrated target scans, we applied five phase-only self-calibration cycles, reaching a r.m.s. 74 μJy bm⁻¹ and a restoring beam of 4.0×1.1 mas. The integrated source flux yields 26 mJy at 5 GHz. Because the observation is only a short snapshot, the UV plane is not sufficiently filled for the longest baselines. To avoid any bias in determining the jet direction, we limit the final image baselines below 3000 km, which is well sampled. The restored beam is 4.0×3.2 mas, and the noise level is 100 μJy bm⁻¹.

2.5. IRAM 30m

We observed NGC 6338 with the IRAM 30 m on 2020 July 21–24 (project 066-20) using the E0 and E2 bands of the EMIR receivers and both horizontal and vertical polarizations. We observed the redshifted CO(1-0) and CO(2-1) lines simultaneously, at 112.194 GHz and 224.388 GHz respectively. Both the FTS and WILMA backends were used. Weather conditions made about half the approved time unusable, but we were able to observe the target for a total of ~8 hr. The focus and pointing of the telescope were calibrated using observations of bright quasars or planets, and the data were reduced using the GILDAS CLASS software (Pety 2005; Gildas Team 2013).

Figure 1 shows the summed CO(1-0) and CO(2-1) spectra of NGC 6338 from IRAM 30 m in the left and right panels, respectively. The vertical axes indicate main beam temperatures (Tmb) in mK, and the spectra are binned to 52 km s⁻¹.

We calculate 3σ upper limits on the molecular gas mass, finding $M_{\text{mol}} \leq 1.4 \times 10^7 M_\odot$ from the CO(1-0) spectrum, and $M_{\text{mol}} \leq 8 \times 10^7 M_\odot$ from the CO(2-1) spectrum, assuming equal excitation temperatures of CO(2-1) and CO(1-0), which means full local thermal equilibrium (LTE). However, for subthermal excitation with $T_{\text{ex}}/T_{\text{K}} \approx 0.5$, we derive an upper mass threshold for CO(2-1) of $1.6 \times 10^8 M_\odot$. Given the uncertainties, we use $1.4 \times 10^8 M_\odot$ as the upper limit for the molecular gas in the southern core, which is a factor of 12 below the mass that would have been predicted based on the

11 http://www.iram.fr/IRAMFR/GILDAS
The H$\alpha$ luminosity of the galaxy and the $L_{H\alpha}$–$M_{mol}$ relation (Salomé & Combes 2003). The beam size of the IRAM 30 m is $\sim 22''$ (HPBW) at our redshifted CO(1-0) frequency and $\sim 11''$ (HPBW) at CO(2-1). The H$\alpha$ filaments in NGC 6338 extend to a $\sim 17''$ radius, but the great majority of the flux is found in the central 5$''$. We therefore assume that all the CO flux is contained within the IRAM 30 m beam.

We note that, while we can only derive an upper limit for the CO (1-0) flux in the southern BCG of 0.94 Jy km s$^{-1}$, it is comparable to the NOEMA detection of CO in the northern BCG of 1.01 Jy km s$^{-1}$ (Pan et al. 2020).

3. Results

We describe the results obtained from the data that have been analyzed: The new uGMRT data cover low frequencies (below 1 GHz) at higher spatial resolution compared to existing LOFAR data (13$''$$7 \times 8''7$ versus 7$''$$9 \times 5''6$ for the band 3 uGMRT data), allowing us to look at feedback cycles of the AGNs in the northern and southern BCG in detail. With the multifrequency radio coverage from 142 MHz to 20 GHz, the SED is parameterized by a self-consistent model, which can even be expanded to 230 GHz. The archival VLBA data give a glimpse at the current state of the AGN.

3.1. Feedback Cycles in the Southern BCG

There are strong indications that the southern BCG has established a feedback cycle that is maintained by the central AGN: O’Sullivan et al. (2019) found X-ray cavities around the core (inner cavities and a potential outer cavity in the E), a strong radio point source in the center of the BCG, and H$\alpha$ filaments. These features are either absent or less pronounced in the northern BCG, which we describe in more detail in Section 3.4. O’Sullivan et al. (2019) did not find extended radio emission in a GMRT pointed observation at 1.39 GHz in the southern BCG of NGC 6338, at least not beyond a small extension of the core to the southwest. However, assuming a typical spectral index for aged radio lobes we expect our new uGMRT data sets to be at least five times deeper and able to detect any signs of past feedback.

3.1.1. Extended Radio Emission

Low-frequency 143 MHz LOFAR data have detected extended emission around the southern core of NGC 6338 (see Birzan et al. 2020, and our Figure 12). The restoring beam size of LOFAR is 13$''$$7 \times 8''7$, which is about three times larger than the uGMRT band 4 data (Table 1), while uGMRT also has sufficient sensitivity to detect the extended emission. Figure 2 shows the radio contours in uGMRT band 3 (middle panel) and uGMRT band 4 (left panel) on an SDSS r-band image. The band 3 and 4 data clearly resolve the structure of this extended emission: We see a pair of lobes in the southeast–northwest direction, which have not been detected at 1.4 GHz with the GMRT (O’Sullivan et al. 2019). The UV coverage of the GMRT data is sensitive to extended emission on scales up to 3$^\prime$4 (band 4) and 4$^\prime$3 (band 3). The southeast lobe extends about 20 kpc, while the northwest lobe extends out to only 14 kpc. Both lobes are detected at high significance (contours in Figure 2 start at 5$\sigma$). The flux density in the southeast lobe is $10.0 \pm 0.1$ mJy at band 3 and $5.1 \pm 0.1$ mJy at band 4, while the other lobe has $11.4 \pm 0.1$ mJy and $6.1 \pm 0.1$ mJy at bands 3 and 4, respectively. The peak emission in the southern BCG coincides with the optical center of the galaxy and is $56.2 \pm 0.1$ mJy bm$^{-1}$ in band 3, and $62.2 \pm 0.1$ mJy bm$^{-1}$ in band 4, yielding a slightly positive spectral index. Given that the flux density at this location might be blended with the lobes, it is only an upper limit for the flux of the central AGN. Next to the center of the AGN, we can identify another, much smaller pair of lobes in the orthogonal direction (southwest to northeast), which we describe in more detail below.

We find some other (distant) radio sources in the nearby field that we can identify using NED (see Figure 2 middle panel) and confirm the accuracy of our astrometric corrections. We do not find other extended sources in the center of this merging group, and none in the outskirts that are related to NGC 6338. The brightest source in the field (136 mJy bm$^{-1}$ in band 3) is about 20$'$$'$ to the west.

The depth of the uGMRT data in both bands allows us to create a spectral index map from 383 to 650 MHz for the southern BCG. Figure 2 (right) shows a map of the spectral index $\alpha$, which we define as $S_\nu \propto \nu^\alpha$, where $S_\nu$ is the flux density at frequency $\nu$. We show the associated error map of
the spectral index in Figure 11. The core of the region exhibits an inverted spectrum with $\sigma_{383-650\text{ MHz}} = 0.34 \pm 0.5$. The spectrum steepens when moving away from the core, and reaches $-1.64 \pm 0.08$ in the southeast and $-1.49 \pm 0.05$ in the northwest.

As shown by the band 3 contours in Figure 2 (right), the steepening does not follow exactly along the trajectory given by the brightness distribution.

The radio lobes in the southern BCG described above mark an older outburst of the BCG. It is expected that these radio-bright relativistic particles evacuate a confined region of the hot gas, which will move to larger radii due to buoyant forces. We tested whether the region containing the radio plasma actually coincides with cavities in the X-ray image by overlaying it with the Chandra residual map (from O’Sullivan et al. 2019, Figure 3 left). O’Sullivan et al. (2019) found a cavity to the SE, and from their X-ray residual map, a less significant depression at a similar distance to the NW can be identified (see outer cavities in Figure 3). We created an azimuthal profile from the Chandra (0.5–2) keV image in an annulus at the distance of the radio lobes (Figure 4). We confirm the eastern cavity (Figure 3) that has been tentatively detected by O’Sullivan et al. (2019). The western cavity shows a dip in the azimuthal profile, but the surface brightness depression is much broader than the eastern cavity. Unlike the eastern cavity, where a rim structure is clearly visible, we cannot find this around the western cavity. Although the radio lobe location matches the surface brightness dip of the western cavity, we can only classify this as a possible X-ray cavity, also due to the complex structure of the whole system.

The eastern cavity and western cavity candidate coincide with the locations of the old radio lobes (SE and NW, labeled as outer cavities). The red contours in Figure 3 are derived from a band 4 image that excludes part of the large-scale emission by applying a minimum UV threshold of 8k$\lambda$, which not only points out the inner lobes mentioned earlier, but also shows only the brighter patches of the outer cavities. The inner lobes are perpendicular to the outer lobes (in projection), and seem to largely fill the strong X-ray inner cavities.

### 3.1.2. Radio Spectrum

In the previous paragraph, we have described the spatial distribution of the extended radio emission, especially in the southern BCG. With our multifrequency coverage, we are able to also analyze the integrated radio spectrum. Therefore, we include more data sets, beyond the two uGMRT bands: We have a low-frequency measurement from LOFAR at 142 MHz, which shows extended emission but does not allow us to cleanly separate it from the central core. We also have several measurements above 1 GHz:

1. The NRAO VLA Sky Survey at 1.4 GHz (NVSS, Condon et al. 1998) with 45″ resolution is sufficient to measure the flux of the integrated emission, but cannot resolve any structure.
2. The VLA FIRST Survey at 1.44 GHz (Becker et al. 1994) provides a spatial resolution of 5″. It allows us to measure the core emission blended with the inner lobes, and is sensitive to detect extended emission on scales up to 2′.
3. The Karl G. Jansky Very Large Array Sky Survey (VLASS; Lacy et al. 2020) at 3 GHz is a currently ongoing survey, which has already completed two epochs with scans of the NGC 6338 field. Its 2′5 spatial resolution allows a clear detection and measurement of the core flux. No extended emission is detected, while it should be able to detect emission on scales up to 1′, which is almost the size of the outer lobes.
4. The VLA has observed the NGC 6338 field at a number of frequencies since 1990, which allows us to track the time variability of the AGN emission. This will be discussed in Section 3.3.2. Here, we describe the spectrum up to 25 GHz and make use of the simultaneous observation in the C, X, Ku, and K bands (4.86 GHz, 8.46 GHz, 14.94 GHz, and 22.46 GHz, respectively) in project AM701 (Table 2). Each band allows a clear flux
measurement, but no band shows signs of extended emission or any deviation from a single point source.

Our modeling of the SED consists of a core emission model and a model for the lobe emission. A simple model that parameterizes the core emission is a power law with a soft absorption part to account for decreasing fluxes at lower frequencies. The physical interpretation of the absorption model is discussed in Section 4.2. In our model for the core emission, we leave the spectral index at low frequencies free to vary, and we also include a variable turnover frequency and a smoothing parameter. The model for the lobe emission is a simple power law.

The fluxes from LOFAR, uGMRT, and NVSS are extracted within an aperture of 1′ radius, which includes all the emission from the outer lobes and the core, but not any emission from the northern BCG. We show these “total” fluxes as black data points in Figure 5, to which the model of the core plus the lobe is fitted. We note that the shortest LOFAR baselines are 90 m at 140 MHz, corresponding to a largest angular scale (LAS) of 1′.3. However, the LOFAR image does not show any emission on scales larger than 1′.5. The uGMRT data sets are imaged from 700 λ, which corresponds to an LAS 4′.9. Therefore, we can safely compare the fluxes measured from LOFAR and uGMRT. However, for the spectral index maps (Figure 2 right), all data sets were imaged with identical UV ranges. The measurements above 2 GHz (shown in blue in Figure 5) detect only the core emission, and therefore only the core model is fitted in this case. The fitting is done with the emcee MCMC framework (Foreman-Mackey et al. 2013) by modeling the likelihood for the two components in a single function. All parameters have flat priors.

The fit with this simple power law for the lobe emission is shown in the left panel of Figure 5. We find that the resulting model fits the data well ($\chi^2_{\text{red}} = 2.5$, dof = 2). The low-frequency index of the core emission is relatively close to the theoretical 2.5, but not above, making synchrotron self-absorption (SSA) a valid possibility. The high-frequency index of $-0.58^{+0.05}_{-0.07}$ is typical for AGNs with active jets. The lobe model with a spectral index of $-1.13^{+0.23}_{-0.3}$ contributes most of the flux to the LOFAR measurement, and about half the flux of the integrated source at uGMRT band 3.

The spatial resolution of the uGMRT data allows us to distinguish the lobe emission from the inner region flux (core plus inner lobes). The lobe flux at 383 MHz is about 21 mJy, while the model for the single power law (green line in Figure 5) predicts about 47 mJy. The flux of the inner core region at the GMRT frequency is also much higher than the simple core model (blue line in Figure 5). This means we are unable to link the derived model components to physical regions. Therefore, we refine the lobe model by adding a second power law component, so that one power law accounts for each set of lobes (inner and outer). We included the flux measurements of the inner region including both the core and the inner lobes, but we do not spatially separate the inner lobes from the core, because the overlap is too large and projection effects would be inevitable. The resulting fit is shown in Figure 5 right: The integrated flux (black) and the core flux (blue) are fit as well as for the simple case. The model for the outer lobe (yellow) agrees with measurements of the outer lobe flux at the uGMRT frequencies, although these measurements have not been included in the fit (yellow data points). The outer lobe model shows a steeper spectrum than the inner lobes ($-1.25^{+0.20}_{-0.22}$ versus $-0.90^{+0.12}_{-0.08}$), indicating an older plasma. This is in agreement with the impression from the spectral index map in Figure 2. The other model components change only slightly when including the second power law for the lobes: The core high-frequency spectral index remains at $-0.58^{+0.05}_{-0.08}$, and the low-frequency spectral index changes only marginally to 1.24$^{+0.12}_{-0.05}$. We also find that the turnover frequency for the core model changes slightly within the uncertainties (from 923$^{+371}_{-191}$ MHz to 849$^{+243}_{-168}$ MHz). The overall fit improves ($\chi^2_{\text{red}} = 1.1$, dof = 4).

3.2. Did the AGN in the Southern BCG Change Its Direction of Feedback?

The new, inner lobes that coincide with the inner X-ray cavities (Figure 3) indicate a change of direction of the feedback provided by the AGN, since they are not aligned with the tentative outer cavities. The change appears to be almost 90° in projection, which is significant.

To understand the current state of the AGN, in particular if the AGN is currently active, we analyzed the archival VLBA

![Figure 5](image_url)
observation that targeted the center of the southern BCG. Our VLBA image (Figure 6) shows a bright source in the center, possibly the core, with R.A. 17:15:22.98 and decl. +57:24:40.31. A fainter point source is located 5.1 mas (about 2.7 pc) to the southwest. Since we do not detect a double-sided jet with a core in the center, we cannot say for sure which of the two sources is the core, because hotspots can exceed the core in flux (e.g., Taylor et al. 1996). However, we can infer an orientation angle from the location of the two sources, which is close to 45° and consistent with the orientation of the inner lobes. We use the CASA task imfit to fit two Gaussian components to the brightness distribution. This results in 21.5 ± 0.2 mJy for the brightest source, and 3.4 ± 0.3 mJy for the source offset to the SW.

The total VLBA detected flux density at 4.98 GHz is 28.7 ± 0.3 mJy. The deepest C-band VLA observation is also very close in time (within a year) and finds a flux of 28.1 ± 0.1 mJy at the effective frequency 6 GHz. Utilizing the spectral index found in the previous section, this converts to a flux density of 31.0 ± 0.1 mJy at the VLBA frequency. This 20% difference in flux between VLBA and VLA could be due to short-term flux variability. We also note that another C-band observation in 2001 obtained the same flux density as the VLBA. But even if 20% of the flux is missed by the VLBA, it means that most of the core emission is on scales smaller than 43 mas (22 pc), which marks the angular size of the shortest VLBA baseline. We are confident that we are not missing other jet emission in the direction, e.g., of the older lobes, and that the change in jet direction is real.

3.3. What is the Current State of Feedback in the Southern BCG?

3.3.1. High-frequency Flux

The VLBA image in Figure 6 suggests a small jet in the northeast–southwest direction. However, the observation is not deep enough to constrain separate spectral indices for the core and jet components, which would be favorable for age estimates. Therefore, we extend the radio spectral analysis presented in Figure 5 to even higher frequencies up to 230 GHz. This allows us to test for an accretion disk model component, such as an advection-dominated accretion flow (ADAF; see, e.g., Mahadevan 1997; Narayan et al. 1998). For example, Sgr A* is far below Eddington luminosity, and the SED from radio to X-rays can be modeled with an ADAF component for the accretion as demonstrated by Yuan et al. (2002). Schellenberger et al. (2020a) confirmed that the ADAF model could account for the high-frequency flux increase in NGC5044, and interpreted this as an active feedback cycle.

The Korean VLBI Network facility comprises three 21 m radio telescopes with baselines from 300 to 500 km. Park et al. (2013) observed NGC 6338 simultaneously at 22 and 42 GHz with two antennas in single-dish mode on 2010 December 31. The fluxes (Figure 7) are much (i.e., more than a factor of 3) higher than what was expected from the VLA measurements and the power-law model. However, Park et al. (2013) note that, for these two measurements, the pointing correction could not be done, because the source was only detected in either the azimuth or elevation cross-scan, but not in both. The source fluxes are therefore unreliable, and it remains unclear if the inconsistent fluxes are due to false measurements or time variability. Therefore, we do not take these two data points into account for a spectral fit.

NGC 6338 has also been observed with the GISMO bolometer camera on the IRAM-30 m telescope in 2012 October by Hogan et al. (2015). The authors showed NGC 6338 to have a flux of 7.3 ± 1.5 GHz at 150 GHz. The authors interpreted the GISMO flux as “flickering at high frequencies or variability.” It is also slightly inconsistent with the reobservation in 2019 by Rose et al. (2021) with the NIKAI2 bolometer on the IRAM-30 m telescope, which found the flux to be 4.5 ± 0.5 mJy at the same frequency as GISMO. It should be noted that here we averaged the two NIKAI2 measurements, which were about 7 months apart and are consistent with each other.

![Figure 6. VLBA image of the southern core with contours at the 5σ, 10σ, 20σ, and 100σ levels. The restoring beam is shown in the lower left corner.](image)

![Figure 7. Modeling of the high-frequency spectrum of the southern BCG. The dashed power law is consistent with all data points except the IRAM/GISMO measurement, which requires an additional ADAF component that does not match the current SMA flux. KVN measurements use a large aperture and might be biased.](image)
In the ADAF model, the flux density is proportional to the accretion rate $\propto r^{4/5}$ for the synchrotron part of the spectrum (Mahadevan 1997). If we interpret the GISMO measurement as indicative of ongoing accretion and model it using an ADAF model (see Figure 7), we find a small accretion rate of $0.01 M_\odot$ yr$^{-1}$ for a black hole mass of $2.9 \times 10^9 M_\odot$ (as determined by Mezcua et al. 2018 from the K band). This accretion model allows us to model the GISMO flux, but it is also inconsistent with NIKA2.

Most recently, our dedicated SMA observation at 230 GHz revealed the current flux to be consistent with the NIKA2 measurement, assuming the power-law spectral index of $-0.53$ (see Figure 7). If the GISMO, NIKA2, and SMA measurements are all taken at face value, one could imagine the accretion rate only affecting the time around 2012 (GISMO measurement) and decreasing to lower values afterward.

### 3.3.2. Time Variability

A time variability of the accretion flow might be linked to the size of the accretion disk. Unfortunately, we have no sufficient time sampling of the lightcurve at mm wavelengths available for NGC 6338, and the time variability study relies on the frequent VLA observations. The VLA frequencies between 1 and 5 GHz will not be affected much by a moderate ADAF component (see Figure 7). However, variability in these bands can be connected to jet disturbance or in-jet shocks from a largely turbulent magnetic field (e.g., Aller et al. 2017; O’Dea & Saikia 2021). Core-dominated flat-spectrum radio AGN typically show the most dramatic examples of intensity and polarization variability. We have analyzed repeated VLA observations (Table 2) of the AGN in the southern BCG, which allows us to construct a lightcurve (Figure 8). Over the past 30 yr, NGC 6338 has been observed six times in C band (blue points in Figure 8) and twice in S band for the VLASS survey (green points in Figure 8). We treat the C-band flux densities as a reference because they provide the best long-term coverage, and we convert VLASS fluxes densities to 5 GHz using the spectral index $-0.53$. We decided to exclude the L-band fluxes here because of the changing contribution from extended emission (inner and maybe outer lobes) in different VLA configurations. The extended emission has only minimal contribution to the flux density at C band in the most compact configuration ($<0.7$ mJy). The only C-band observation in D configuration was taken in 2001, where we find the lowest flux. Subtracting any extended emission will result in an even lower point-source flux and increase the variability. The overall scatter (standard deviation, not taking into account the time of observation) between the C-band observations is 3.8 mJy, exceeding by far the typical statistical uncertainty (average r.m.s) of 0.2 mJy. The same is true for the L-band observation, where the scatter is 5.4 mJy and the average r.m.s about 1 mJy. The smoothed lightcurve over all fluxes shown as black line in Figure 8 shows a decrease in flux until 2005 and a rise afterward. The region around this turnover is not sampled well. The magenta line in Figure 8 shows the relative change in flux per year based on the smoothed curve, which also shows the constant 2% decrease until 2005 and the peak of 6% increase shortly after that. The typical variability is on a timescale of years, but we lack good short-term sampling.

### 3.4. Did the Feedback Stop in the Northern BCG?

The merging group toward the north appears to host two bright galaxies in the center (see Figure 2). We detect radio emission associated with the northern of the two in both uGMRT bands with high significance: 1.4 $\pm$ 0.1 mJy at band 3 and 0.59 $\pm$ 0.10 mJy at band 4. This indicates a very steep spectrum source with $\alpha_{0.383-650}$ MHz $= -1.6_{-0.4}^{+0.3}$. Because the LOFAR flux at this location is only $3.2 \pm 0.3$ mJy, the spectrum of the northern source is likely bent, e.g., due to aging of radio lobes that are not resolved here. The spectral index between LOFAR and uGMRT band 3 is significantly flatter: $\alpha_{0.383-0.12}$ MHz $= -0.3_{-0.12}^{+0.12}$. No emission is detected in any VLA observation (L, S, or C band), but the noise levels do not allow us to claim an upper limit for an even steeper spectral index toward these high frequencies.

O’Sullivan et al. (2019) found several features in the X-ray residual map, such as an emission aligned in a southeast–northwest oriented bar, with depressions in the X-ray wavelength on either side of the bar. The depression in the southwest appears to be enclosed by a brighter rim, marking it as a likely cavity. However, we find that the faint radio emission is not aligned with the cavities; it seems to extend from the center of the bar toward the south-southeast (see...
The X-ray center, the brightest part of the southeast–northwest bar, is offset to the north of the optical center of the galaxy (blue mark in Figure 9). The uGMRT radio emission in the northern core has a head-tail structure in Band 4, with the tail toward the north and the head coinciding with the optical center. Some fainter emission is offset to the southeast, and the Band 3 data cover this blob as well. The projected image in Figure 9 indicates that the Hα-emitting gas and the radio plasma share a similar direction. Lin et al. (2017) and Pan et al. (2020) show IFU data indicating that the Hα filaments extend from the optical center to the green region in Figure 9.

The locations of the warm gas and the lobes from the AGN give a consistent picture, while the X-ray cavities are offset from this. However, since the merger is mainly along the line of sight, there are strong projection effects to be considered here: The main extent of the radio tail is likely not to the north, but instead along the line of sight.

4. Discussion

NGC 6338 is a violent merger with two visible cores. The merger is mostly along the line of sight, with an offset of a few hundred kpc. We have examined the visible signs of feedback in the southern BCG: We have detected a set of old lobes in our deep uGMRT observations at 383 and 650 MHz, which extend 45″ (24 kpc) in the southeast and northwest directions. The radio lobes match the location of X-ray cavities in the IGM.

4.1. Age of the Past Feedback Cycle

We observe strong features of AGN feedback in the southern BCG of the merging galaxy group NGC 6338, such as X-ray cavities filled with radio lobes, a smaller set of lobes, and a radio-bright core that seems to have a parsec-scale jet in the IGM. The outer lobes are spatially resolved in both GMRT bands, allowing us to construct a spectral index map (Figure 2).

The uncertainties were computed assuming a 10% flux calibration uncertainty of uGMRT (e.g., Kal et al. 2022). We use the spectral index and the outer lobe brightness from our spectral modeling (Figure 5 right), which yields $B = 3.1 \pm 0.5 \mu G$. This magnetic field is not well constrained, mainly due to the uncertainties in the break frequency, but the strength is typical for clusters and groups (Dolag et al. 2008; Donnert et al. 2018).

The outer lobes are spatially resolved in both GMRT bands, allowing us to construct a spectral index map (Figure 2). However, since in-band spectral measurements are not possible with the available GMRT data, we are unable to measure a potential spectral break from just two frequencies. Instead, we can infer a spectral break frequency when we make assumptions on the expansion history of the lobes. If the lobe emission is locally well described by the JP model (Jaffe & Perola 1973), a widely used spectral aging model assuming a single injection of electrons, and a constant expansion velocity in the plane of the sky from the central AGN is assumed, the spectral break frequency will be proportional to the inverse of the square of the distance $t_{\text{break}} \propto d^{-2}$, which has also been demonstrated in Murgia et al. (2002), Murgia (2003), Parma et al. (2007), and Giacintucci et al. (2008). However, in the case of a continuous injection of electrons by the jets into the radio lobes, the emission can be modeled by a continuous injection (CI) model, which includes an injection spectral index of the youngest electrons that show up in the low-frequency part of the spectrum, and above the break frequency, a second, steeper power law. If the injection occurs in phases, as it can be assumed to do for an AGN duty cycle, it is common practice to use the Cl_{OFF} model (see Murgia et al. 2011), which has an additional parameter for the fraction of time that the source is active.

With the available information from our radio analysis, we are able to quantify the history of the feedback in NGC 6338. Qualitatively, we find a set of older lobes connected with the AGN in the southern BCG, and there are also strong indications of a smaller set of lobes from the integrated spectrum and the high spatial resolution radio data. These smaller lobes are expected to be younger, due to the slightly flatter spectrum ($\alpha = -0.9$ versus $-1.3$ for the larger lobes), and are orthogonal to the larger lobes in the projection on the sky. The projected direction of the younger lobes agrees with the extent seen in the VLBA image, which could indicate that these are still powered by the current AGN feedback cycle.
bands. Right: uGMRT spectral index from 383 to 650 MHz vs. the distance from the core of the southern BCG. This allows to determine the break frequency of the new lobe is about 25% of the trajectory of the old lobes. The distance of the outer edge of the new lobes by scaling the previously determined age by the relative size of the new lobes. The distance of the outer edge of the new lobe is about 25% of the trajectory of the old lobes (see Figure 3), which means that the age of the new lobes is 50 ± 18 Myr.

4.2. Current State of the AGN

The central radio source in the southern BCG, responsible for the feedback cycles imprinted in the IGM and extended radio emission, has to be understood in order to obtain a fully consistent picture of the feedback in a group merger. The radio spectrum is a power law over almost three orders of magnitude, and the spectral index of $\alpha = -0.58$ can be confirmed through our recent SMA observation at 225 GHz. A flux increase at mm wavelengths was indicated through the 2012 IRAM/GISMO observations, which could not be confirmed with our recent SMA observation. A luminous ADAF component, which could explain such a flux increase, could therefore not be confirmed. The time variability of the ~GHz flux found in the VLA observations (Figure 8), roughly coincides with the time of IRAM/GISMO, which could point to an ongoing feeding/feedback process.

Two absorption mechanisms are typically discussed in literature (e.g., Kellermann & Pauliny-Toth 1969; O’Dea 1998; O’Dea & Saikia 2021): free–free absorption (FFA) in an ionized gas surrounding the source, and self-absorption of the synchrotron emitting electrons (synchrotron self-absorption; SSA). Both processes cause an inverted spectrum at low frequencies. In the case of SSA, the theoretically expected spectral index of 2.5 is rarely observed. The SSA mechanism requires magnetic fields in the center of the radio source roughly consistent with minimum pressure (O’Dea 1998), which makes SSA often a preferred mechanism, while FFA requires very high thermal electron densities.

AGN is in the dying phase without injection of new charged particles—although the uncertainty on this number is again substantial, around 50%. If we assume the old and new lobes share the same expansion velocity, we can measure the age of the new lobes by scaling the previously determined age by the relative size of the new lobes. The distance of the outer edge of the new lobe is about 25% of the trajectory of the old lobes (see Figure 3), which means that the age of the new lobes is 50 ± 18 Myr.

It remains difficult to distinguish between FFA and SSA for peaked spectrum sources (e.g., Snellen et al. 2000; Edwards & Tingay 2004; Callingham et al. 2017; Ross et al. 2021). At lower radio frequencies (around 800 MHz), we find a turnover of the spectrum, from a spectral index of $-0.58$ above 1 GHz toward $>1.5$ at lowest frequencies. This approaches the homogeneous, opaque synchrotron source spectrum of 2.5.

The VLBA image in Figure 6 shows only two components, one of which is assumed to be a jet while the other one likely the core. The visible jet is likely inclined toward the observer, making the current jet system unaligned with the plane of the sky. Because we are unable to distinguish which component is the jet and which is the core, we cannot state the orientation. However, the older lobes in the uGMRT image (Figure 3) appear more similar in brightness, supporting the assumption that the older outburst did not have a strong line-of-sight component.

5. Summary

NGC 6338 is one of the most violent group–group mergers known to date. We have examined the past and ongoing feedback processes induced by the AGN in the southern BCG. Interestingly, the feedback does not seem to stop, but its direction, traced by the radio lobes and jets, has changed. While the northern group is slightly less massive and also hosts a less massive BCG with weak signs of feedback, the southern BCG provides many features to be explored. We find:

1. a set of old and new lobes (radiative age of 200 Myr and 50 Myr), which seem to coincide with X-ray cavities;
2. a change in projected alignment of the two feedback cycles, which is almost 90°;
3. an SED from 144 MHz to 235 GHz that can be modeled with a power law for each sets of lobes and a power law with a soft turnover representing the core emission;
4. larger SE-NW lobes that have a slightly steeper spectral index than the smaller SW-NE lobes ($-1.3$ versus $-1.1$), and the spectral index steepening of the larger lobes points toward a radiative age of about 200 Myr;
5. a small, parsec-scale jet in the VLBA image, with a direction similar to those of the new radio lobes, which strengthens the assumption of a recent shift in feedback direction and that the newly inflated cavities might still be powered;

6. radio emission in the core that is consistent with typical spectral index of \(-0.58\) and currently shows no indications of steepening.

For a complete picture of the feedback processes, especially on the galaxy group level, we need to understand the current and past AGN feedback cycles in various environments. Through the wealth of high-quality, multiwavelength data from radio to X-rays, NGC 6338 offers the possibility to look at the feedback process in a violent group–group merger in the pre-core-passage phase.

The results highlight the importance of a good understanding of the radio/mm SED, and they reveal another case with a recent change in the feedback directional axis.

A future, high spectral resolution X-ray imaging instrument such as Athena X-IFU (Barret et al. 2013) will be able to provide significant insights regarding the gas cooling near the center of this group.

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Appendix A
Spectral Index Error Map

We have shown in Figure 2 (right panel) that we can derive a spectral index map from the two band uGMRT observations at 383 and 650 MHz. Figure 11 shows the corresponding error map of the spectral index, which demonstrates that the aged lobes have a significantly steeper spectrum.

Figure 11. Spectral index error map of uGMRT band 3 and 4 data. The white contours show the emission at 383 MHz at 5\(\sigma\), 25\(\sigma\), and 125\(\sigma\). The restoring beam is shown in the lower left corner.
Appendix B

LOFAR Image

Our radio spectrum of the southern core (Figure 5) extends to the lowest frequencies at 144 MHz provided by LOFAR. Figure 12 shows the LOFAR image of the southern core, which clearly detects the outer lobes.

Figure 12. LOFAR image of the southern BCG at 143 MHz with contours at 5σ, 25σ, and 125σ; see also Birzan et al. (2020). The shortest LOFAR baselines are 90 m at 140 MHz, corresponding to a largest angular scale of 1.3. However, the LOFAR image does not show any emission on scales larger than 1.5.

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