Interactions among intermediate redshift galaxies

The case of SDSS J134420.86+663717.8

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ABSTRACT

We present the properties of the central supermassive black holes and the host galaxies of the interacting object SDSS J134420.86+663717.8. We obtained optical long slit spectroscopy data from the Large Binocular Telescope using the Multi Object Double Spectrograph. Analysing the spectra revealed several strong broad and narrow emission lines of ionised gas in the nuclear region of one galaxy, whereas only narrow emission lines were visible for the second galaxy. The optical spectra were used to plot diagnostic diagrams, deduce rotation curves of the two galaxies, and calculate the masses of the central supermassive black holes. We find that the galaxy with broad emission line features has Seyfert 1 properties, while the galaxy with only narrow emission line features seems to be star-forming in nature. Furthermore, we find that the masses of the central supermassive black holes are almost equal at a few times 10⁷ M☉. Additionally, we present a simple N-body simulation to shed some light on the initial conditions of the progenitor galaxies. We find that for an almost orthogonal approach of the two interacting galaxies, the model resembles the optical image of the system.

Key words. galaxies: interactions – galaxies: active – galaxies: kinematics and dynamics – galaxies: starburst – galaxies: evolution – methods: numerical

1. Introduction

Interactions play an important role in the evolution of galaxies. It is generally accepted that smaller galaxies in the past merged to form larger galaxies (White & Rees 1978; Kauffmann et al. 1993; Cole et al. 2000; Casteels et al. 2014). The gas content in these galaxies was affected as a result of this process. Gas-rich galaxies interacted with one another, causing the gas and dust content to get funneled through to the centre, leading to bursts of star formation and enabling the black holes in the centres of galaxies to start accreting material (Barnes & Hernquist 1991, 1996; Mihos & Hernquist 1994, 1996; Di Matteo et al. 2005, 2012; Hopkins et al. 2005a,b; Cox et al. 2008; Lotz et al. 2008, 2010a,b; Ellison et al. 2013; Torrey et al. 2014; Casteels et al. 2014). Accretion onto the central super massive black hole (SMBH) and the starburst phase leads to the depletion of gas in the progenitor galaxies and the merger remnants end up gas-poor (Springel et al. 2005; Johansson et al. 2009; Hopkins et al. 2010a).

Early surveys and catalogs by Vorontsov-Velyaminov (1959), Arp (1966), Zwicky et al. (1968) list many galaxies as distorted or irregular. Pfleiderer & Siedentopf (1961), Pfleiderer (1963), Yabushita (1971), Toomre & Toomre (1971), Clutton-Brock (1972a,b), Wright (1972), Eneev et al. (1973), Barnes & Hernquist (1992) showed that the distortions could be caused by the influence of the gravitational potential of one galaxy on the gas and dust content of the other galaxy using simple models and three-body interactions. Over the years, many attempts have been made to study the merger rate over cosmic time. For example: Mantha et al. (2018) analysed a sample of 9800 massive (Mstellar ≥ 2 × 10¹⁰ M☉) galaxies spanning 0 < z < 3, and found that the merger rate fraction increases from z = 0 to 0.5 < z < 1 before decreasing at 2.5 < z < 3, indicating a turnover at z ≈ 1. Hopkins et al. (2010b) provides a good review of the different models used to study merger rates theoretically.

Another interesting point to consider while studying interacting galaxies is the influence they have on triggering active galactic nuclei (AGN). While traditionally, the theoretical view has been that mergers are the predominant mechanism responsible for black hole growth and AGN activity, some theoretical studies predict the requirement of other processes along with merging to drive nuclear activity (Fanidakis et al. 2012; Hirschmann et al. 2012). Steinborn et al. (2018) conclude that while mergers increase the probability for nuclear activity, the role of mergers causing nuclear activity in the overall AGN population is still minor (<20%). This is also the case with observational studies, with some of them finding that mergers play a minor role in triggering luminous AGN (Villforth et al. 2017; Hewlett et al. 2017), while other studies find that mergers are the dominant mechanism for driving AGN activity (Urrutia et al. 2008; Hopkins & Hernquist 2009; Treister et al. 2012; Glikman et al. 2015; Fan et al. 2016).
The highly energetic phenomena known as AGN emit brightly over the entire electromagnetic spectrum. They can be broadly classified as Type 1 and Type 2 AGN based on the respective presence or absence of broad emission lines in their spectra. Antonucci (1993) put forth an AGN unification model, wherein Type 1 and Type 2 AGN are the same type of object, with the difference appearing relative to the orientation of the observer. If the unification scheme holds true, there should be no significant difference in the external environment of Type 1 and Type 2 AGN. However, Dultzin-Hacyan et al. (1999), Koulouridis et al. (2006), Jiang et al. (2016) found more Type 2 galaxies than Type 1 galaxies in close galaxy pairs, leading to the suggestion that instead of a unified AGN model, galaxy interactions could result in evolution of galaxies from star-forming to Type 2 and finally to Type 1. Gordon et al. (2017) find that up to a pair separation of 50 kpc h^{-1}, there is no difference in the AGN found in pairs based on the AGN type, with an excess of Type 2 AGN at separations lesser than 20 kpc h^{-1}. They suggest that either the unified model breaks down in the case of close gravitational interactions or that the interaction between galaxies drives more dust towards the nucleus, causing the obscuration to be more probable. Additionally, Ricci et al. (2017) find that the fraction of Compton-thick AGN in late merger galaxies is higher compared to the local hard X-ray selected AGN. They conclude that late stage mergers of galaxies suffer greater obscuration as material is most efficiently funnelled to the inner parsecs from the outer scales and the classical AGN unification model cannot sufficiently explain this phenomenon.

The lifetimes of interactions among galaxies are measured in the order of 10^8 years (Struck 1999). It is, therefore, impossible for us to study a particular case in the entirety of the process. Every case available to us is a cosmic “snapshot” of a particular phase in the long series of interactive events, and as such, yields information and helps to better our understanding of galaxy mergers. Studying different pairs of galaxies at different stages in their interaction aids in putting together a coherent picture of the series of events. Another important tool that helps in increasing our knowledge is simulations of galaxy interactions. Observations help make the simulations more detailed while simulations help to interpret the observations.

SDSS J134420.86+663717.8 is a pair of interacting galaxies that is located at an intermediate redshift of approximately z ~ 0.128. The pair derives its name from the Sloan Digital Sky Survey catalogue number. Previously, they were cataloged as a clumpy source by several surveys like the Infrared Astronomical Satellite (IRAS), the Wide-field Infrared Survey Explorer (WISE), the Two Micron All Sky Survey (2MASS), the ROentgen SATellite (ROSAT) survey, and the Palomar Schmidt 48-inch telescope survey. Table 1 presents the literature values of luminosity and photometry for SDSS J134420.86+663717.8. The Sloan Digital Sky Survey (SDSS) provides a significantly improved picture of the galaxies. The two nuclei are well resolved and tidal distortions are clearly visible (see Fig. 1). The orientation and size of the tidal tails hint at an orthogonal interaction between the progenitor galaxies. The SDSS website lists some information about the larger of the two nuclei, which we shall call nucleus A, but provides no information for nucleus B. Nucleus A is classified as a quasi-stellar object (QSO) by SDSS (Schneider et al. 2003), as a Seyfert 1 galaxy by Zuther et al. (2012), and as a Seyfert 1.5 galaxy by Paturel et al. (2003) and Moran et al. (1996). Zuther et al. (2012) also note that SDSS J134420.87+663717.6 is an interacting galaxy and the pair shows 2.70 ± 0.40 mJy peak flux at 20 cm (taken from the NVSS 20 cm survey), L_20 = 5 × 10^{11} L_⊙, and log M_BH = 7.6 (taken from Greene & Ho 2007). However, they could not detect any compact flux density at 18 cm with the Multi-Element Radio Linked Interferometer Network (MERLIN). They conclude that the radio emission was likely dominated by extended star formation since it is an infrared (IR) luminous galaxy. Moran et al. (1996) provide values for the flux and luminosity of SDSS J134420.86+663717.8 (or IRAS F13429+6652), as well as Info IRAS catalogue name) in the X-ray and far infrared (FIR) regions to be F_X = 4.88 × 10^{-15} erg s^{-1} cm^{-2}, L_X = 3.87 × 10^{43} erg s^{-1}, F_FIR = 2.18 × 10^{-10} erg s^{-1} cm^{-2}, and L_FIR = 1.73×10^{48} erg s^{-1}, respectively. The X-ray luminosity was calculated using ROSAT observations over the energy range between 0.1–2.4 keV.

As an on-going merger of two intermediate redshift, almost orthogonal galaxies, SDSS J134420.86+663717.8 is a subject of interest as a case study for orthogonal interactions of galaxies. This work focuses on studying the spectra of the two nuclei in the optical wavelength regime and analysing this data. In addition, we use a simple N-body simulation to infer the initial conditions of the host galaxies before the interaction, based on their morphology.

This paper is organised as follows. We present details about the observations and data reduction in Sect. 2. In Sect. 3, we detail the process of spectral extraction and present the optical spectra of the two nuclei. Further on, we mention the results from emission line fits. We analyse the spectra in detail and list some of the properties of the galaxies in Sect. 4 and present an N-body simulation to model a SDSS J134420.86+663717.8 look-alike in Sect. 5. Finally, we summarise the paper and provide some concluding remarks in Sect. 6.

2. Observations and data reduction

SDSS J134420.86+663717.8 was observed using the Multi-Object Double Spectrograph (MODS) at the Large Binocular Telescope (LBT) located at an altitude of approximately 3200 m on Mount Graham, United States (Pogge et al. 2010). The LBT has a binocular design and consists of two 8.4 m wide mirrors mounted side-by-side with a centre-to-centre distance of 14.4 m, such that it has a combined collecting area of an 11.8 m telescope. MODS are a pair of seeing-limited low to medium resolution, two-channel, identical spectrographs: MODS1 and MODS2. They are mounted at the direct Gregorian foci of the twin LBT mirrors. A dichroic splits the light into red and blue optimised spectrograph channels, such that the data corresponding to an object is obtained from four different channels: MODS1 B, MODS1 R, MODS2 B, and MODS2 R. MODS can be used for imaging, long-slit and multi-object spectroscopy. It has a field-of-view of 6′ × 6′. The wavelength range for MODS is from 3000 Å to 10 000 Å. We used MODS in long slit spectroscopy mode to obtain the data on May 13, 2016. The exposure time for each spectrum was 600 s, and the object was observed thrice, with a total exposure time of 1800 s. In

http://skyserver.sdss.org/dr15/en/tools/explore/Summary.aspx?id=1237651273514745920

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The LBT is an international collaboration among institutions in the United States, Italy, and Germany. LBT Corporation partners are: The University of Arizona on behalf of the Arizona Board of Regents; Instituto Nazionale di Astrofisica, Italy; LBT Beteiligungsgesellschaft, Germany, representing the Max-Planck Society, The Leibniz Institute for Astrophysics Potsdam, and Heidelberg University; The Ohio State University, and The Research Corporation, on behalf of The University of Notre Dame, University of Minnesota, and University of Virginia.
Table 1. Photometry values for SDSS J134420.86+663717.8.

| Spectral region | Band    | Apparent mag or flux | Reference |
|-----------------|---------|-----------------------|-----------|
| Ultraviolet     | NUV (GALEX) AB | 17.0747 ± 0.0326211 mag | 1 |
| Visual          | i (SDSS Petrosian) AB | 15.546 ± 0.012 asinh mag | 2 |
| Near-infrared   | Ks      | 12.747 ± 0.079 mag     | 3 |
| Mid-infrared    | 12 microns (IRAS) | <5.397e−02 Jy           | 3 |
| Far-infrared    | 60 microns (IRAS)  | 4.074e−01 ± 9% Jy       | 4 |
| Radio           | 1.4 GHz | 3.2 ± 0.5 mJy          | 5 |

Notes. Credit: NED.

References. (1) Seibert et al. (2012); (2) Schneider et al. (2002); (3) Cutri et al. (2013); (4) Moshir et al. (1990); (5) Condon et al. (1998).

3. Emission line fits and results

We extracted one-dimensional spectra of nuclei A and B from the reduced two-dimensional spectra. This was done by choosing an aperture of approximately 1 arcsec on the spatial axis for each nucleus and then extracting along the wavelength axis. Additionally, we chose an aperture of approximately 8 arcsec and extracted spectra along each pixel row (1 pixel = 0.123 arcsec for MODS Red and 1 pixel = 0.120 arcsec for MODS Blue) in order to study the intensity distribution of the two nuclei. The continuum was fit with a line and all broad emission lines were fit using multiple Gaussian functions, while the narrow emission lines were fit using single Gaussian functions using the Levenberg-Marquardt algorithm, non-linear least-squares minimisation and curve-fitting for Python (LMFIT; Markwardt 2009; Newville et al. 2016).

3.1. Optical spectrum of nucleus A

Figures 2 and 3 show the optical spectrum of nucleus A. The continuum emission is overlaid by several emission lines. Stellar absorption features are not detected. Broad H\textsc{i} emission features are clearly visible. The break in the wavelength axis reproduces the split between the blue and red beams due to the dichroic. Gaussian fits to the emission lines helped in determining the full width at half maximum (FWHM) of the various emission lines (see Fig. 4 for an example of the spectrum fit with Gaussian functions). In order to determine the number of Gaussian components to fit, we started with, for example, three narrow Gaussian components and one broad component for the case of the H\textsc{a} + [N\textsc{ii}] complex. We used visual inspection as well as the $\chi^2$ values of the Gaussian fitting module to determine the number that was the best fit to the data, which in our case was two broad H\textsc{a} components and three narrow components corresponding to [N\textsc{ii}],6548, H\textsc{a}, and [N\textsc{ii}],6583, respectively. The choice was obvious: an additional broad component is required to fit the extended [N\textsc{ii}],6548, H\textsc{a}, and [N\textsc{ii}],6583 wing towards longer wavelengths. The three narrow components are needed to fit the three narrow line features related to the [N\textsc{ii}],6548, H\textsc{a}, and [N\textsc{ii}],6583 lines, respectively. Hence, our choice comprises only the most necessary components. Table 2 lists the different emission lines observed in the spectrum, their flux values and FWHM. The average redshift of nucleus A, as calculated using the central positions of various

\[ \chi^2 \text{ value for only one broad component is 1.19, whereas we find a } \chi^2 \text{ value of 0.32 for two broad components.} \]
emission lines is $0.1279 \pm 0.0002$ ($\sim 38370$ km s$^{-1}$). The velocity corresponding to the redshift is the $cz$ value. The FWHM of the broad components of the H$\alpha$ and H$\beta$ recombination lines are $1715 \pm 14$ km s$^{-1}$, $5317 \pm 56$ km s$^{-1}$, $1944 \pm 55$ km s$^{-1}$, and $2507 \pm 31$ km s$^{-1}$, respectively. The FWHM of the narrow components of the H$\alpha$ and H$\beta$ recombination lines are $256 \pm 3$ km s$^{-1}$ and $335 \pm 6$ km s$^{-1}$, respectively. These FWHM values fall in the range of 1000–6000 km s$^{-1}$ for broad HI lines in Seyfert 1 galaxies, and 300–800 km s$^{-1}$ for narrow lines in both classes of Seyfert galaxies, as specified in Osterbrock & Pogge (1985).

### 3.2. Optical spectrum of nucleus B

Figures 5 and 6 show the optical spectrum of nucleus B. Several stellar absorption features are clearly visible along with some emission lines. Nucleus B shows fewer emission lines compared to nucleus A. No broad emission features are noticeable. Table 3 lists the different emission lines, their flux and FWHM values. The FWHM of the narrow H$\alpha$ and H$\beta$ recombination lines are $250 \pm 2$ km s$^{-1}$ and $256 \pm 16$ km s$^{-1}$, respectively. Some stellar absorption can be seen at the H$\beta$ line. The stellar absorption lines were fit using the “penalised Pixel-Fitting” (pPXF; Cappellari 2017; Cappellari & Emsellem 2004) method, and were taken into consideration while estimating emission line fluxes (see also, Sect. 4.3.2). The average redshift calculated from the central positions of various emission lines is $0.1285 \pm 0.0001$. The plots of spatial position versus intensity for H$\alpha$ and the continuum show that both of them peak at the same point, which we consider to be the position of the central nucleus. We use this to estimate that the systemic redshift of nucleus B is the redshift value displayed by the hydrogen recombination lines at the central position of nucleus B, that is, 0.1285. However, interestingly, the redshift of the [O$\text{III}$] $\lambda$5007 is smaller at 0.1282 ($\sim 38$ 460 km s$^{-1}$), whereas the redshift of the [O$\text{II}$] $\lambda$3727 line is larger at 0.1288 ($\sim 38$ 640 km s$^{-1}$) compared to the mean redshift of 0.1285 ($\sim 38$ 550 km s$^{-1}$). The velocities corresponding to the redshifts are the $cz$ values. [O$\text{II}$] $\lambda$3727 is considered to be a good tracer for star formation. However, Yan et al. (2018) state that [O$\text{II}$] emission in galaxies could have other possible sources like AGN, fast shock waves, post-asymptotic giant branch (AGB) stars, and cooling flows. The comparatively higher value of redshift could arise from star formation in cool molecular clouds accumulated due to cooling flows. Boller et al. (1998) categorise SDSS J134420.86+663727.8 as a source of diffuse X-ray emission. The X-ray emission is suggested to be indicative of cooling flows. If the cooling flow is rapid, an inflow of gas is created to satisfy the condition of hydrostatic equilibrium. The lower redshift associated with the [O$\text{III}$] $\lambda$5007 line could arise due to emission resulting from an outflow. On checking the value of its FWHM, we notice that it is $429 \pm 35$ km s$^{-1}$, which is higher than the FWHM values of the H$\alpha$ and H$\beta$ lines. The [O$\text{III}$] $\lambda$5007 emission line is usually associated with outflows in the narrow line region (NLR). In such cases, the [O$\text{III}$] $\lambda$5007 profile exhibits a blue asymmetry, in that the peak of the line is
skewed blue-ward. However, in our case, the \([\text{O} \text{III}] \lambda 5007\) line
is not reliable since it falls towards the end of the blue spectrum, and is very noisy and weak. Thus, we refrain from drawing any concrete conclusions based on the redshift and shape of the \([\text{O} \text{III}] \lambda 5007\) line.

4. Discussion

Once we obtained the optical spectra of both the galaxies along with the flux values of the different emission lines, we could use this information to deduce some properties associated with the individual galaxies. We discuss our findings in the subsections below. Having this knowledge at hand is useful to reconstruct the picture of the interaction (e.g., while using simulations).

4.1. Diagnostic diagrams

We use the diagnostic diagram originally proposed by Baldwin, Phillips and Terlevich (Baldwin et al. 1981), along with two other diagnostic diagrams which are discussed by Veilleux & Osterbrock (1987). The diagnostic diagrams are essentially a set of three different plots of the ratios of the fluxes of emission lines that are close enough to each other in wavelength to render reddening ineffective. They are used to determine the excitation mechanisms of the gas, and thereby they help us to distinguish between AGN and star-forming galaxies (Kewley et al. 2019). The different excitation mechanisms responsible for line emission could be normal H\text{II} regions, planetary nebulae, objects photoionised by a harder radiation field, AGN, shocks, and low-ionisation nuclear emission-line region (LINER) emission. The Eqs. (1)–(3) (Groves & Kewley 2008) define the curves in the diagrams which separate the AGN from star-forming galaxies (see the plots in Fig. 7). The emission lines used are \([\text{O} \text{III}] \lambda 5007, \text{H}\beta, [\text{N} \text{II}] \lambda 6583, \text{H}\alpha, [\text{O} \text{I}] \lambda 6300, [\text{S} \text{II}] \lambda 6716 and [\text{S} \text{II}] \lambda 6731.

\[
\log([\text{O} \text{III}]/\text{H}\beta) = 0.61/(\log([\text{N} \text{II}]/\text{H}\alpha) - 0.47) + 1.19. \quad (1)
\]
\[
\log([\text{O} \text{III}]/\text{H}\beta) = 0.72/(\log([\text{S} \text{II}]/\text{H}\alpha) - 0.32) + 1.30. \quad (2)
\]
\[
\log([\text{O} \text{III}]/\text{H}\beta) = 0.73/(\log([\text{O} \text{I}]/\text{H}\alpha) + 0.59) + 1.33. \quad (3)
\]

Additionally, there is a curve (Eq. (4)) proposed by Kauffmann et al. (2003), which provides another delineation between AGN

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**Table 2. Values for nucleus A.**

| Emission line | Observed wavelength (Å) | Uncertainty in wavelength (Å) | Flux value \(\times 10^{-16}\) erg s\(^{-1}\) cm\(^{-2}\) | Uncertainty in flux \(\times 10^{-16}\) erg s\(^{-1}\) cm\(^{-2}\) | FWHM (km s\(^{-1}\)) | Uncertainty in FWHM (km s\(^{-1}\)) |
|---------------|-------------------------|-------------------------------|---------------------------------|---------------------------------|-----------------|-------------------------------|
| [O II] \lambda 3727 | 4204.01 | 0.05 | 7.45 | 0.44 | 438 | 9 |
| H\beta narrow | 4894.82 | 0.09 | 3.55 | 0.54 | 330 | 16 |
| H\beta broad | 4903.44 | 0.52 | 2.01 | 0.43 | 3652 | 86 |
| H\alpha narrow | 5482.47 | 0.04 | 8.99 | 0.49 | 335 | 6 |
| H\alpha broad1 | 5477.49 | 0.24 | 9.84 | 0.28 | 1944 | 55 |
| H\alpha broad2 | 5510.64 | 0.29 | 4.84 | 0.06 | 2507 | 31 |
| [O III] \lambda 4959 | 5591.68 | 0.06 | 6.27 | 0.55 | 407 | 8 |
| [O III] \lambda 5007 | 5645.88 | 0.02 | 20.1 | 0.23 | 430 | 3 |
| [He I] \lambda 5876 | 6630.27 | 1.09 | 4.35 | 0.04 | 3022 | 94 |
| [O I] \lambda 6300 | 7105.77 | 0.51 | 0.79 | 0.07 | 202 | 49 |
| [N II] \lambda 6583 | 7385.54 | 0.09 | 6.89 | 0.15 | 287 | 14 |
| H\alpha narrow | 7401.65 | 0.01 | 31.9 | 0.16 | 256 | 3 |
| H\alpha broad1 | 7397.88 | 0.10 | 38.42 | 0.42 | 1715 | 14 |
| H\alpha broad2 | 7410.05 | 0.45 | 41.88 | 0.86 | 5317 | 56 |
| [N II] \lambda 6583 | 7425.12 | 0.03 | 14.2 | 0.68 | 192 | 5 |
| [S II] \lambda 6716 | 7574.90 | 0.09 | 4.39 | 0.21 | 235 | 17 |
| [S II] \lambda 6731 | 7591.79 | 0.09 | 4.45 | 0.05 | 248 | 18 |

**Notes.** All uncertainties are the 1\(\sigma\) standard error values. The values stated are calculated for an aperture of 1 arcsec.
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Fig. 5. One-dimensional observed optical spectrum of SDSS J134420.86+663717.8 nucleus B in the wavelength range 4000–5700 Å. The observed emission and absorption lines have been marked by vertical red dotted lines and named. The aperture size for spectral extraction is 1 arcsec. The wavelength axis depicts the observed wavelength.

Table 3. Values for nucleus B.

| Emission line | Observed wavelength (Å) | Uncertainty in wavelength (Å) | Flux value (10^{-16} erg s^{-1} cm^{-2}) | Uncertainty in flux (10^{-16} erg s^{-1} cm^{-2}) | FWHM (km s^{-1}) | Uncertainty in FWHM (km s^{-1}) |
|---------------|--------------------------|-------------------------------|------------------------------------------|-----------------------------------------------|----------------|----------------------------------|
| [O ii]λ3727   | 4206.95                  | 0.12                          | 1.50                                     | 0.27                                          | 383            | 20                              |
| [O ii] λ5007  | 5486.34                  | 0.13                          | 1.35                                     | 0.16                                          | 256            | 16                              |
| [O ii] λ5007  | 5648.63                  | 0.28                          | 0.62                                     | 0.06                                          | 429            | 35                              |
| [N ii] λ6548  | 7108.99                  | 0.64                          | 0.19                                     | 0.02                                          | 404            | 65                              |
| [N ii] λ6548  | 7389.56                  | 0.11                          | 1.14                                     | 0.04                                          | 323            | 10                              |
| Hα_narrow    | 7406.12                  | 0.01                          | 7.51                                     | 0.32                                          | 250            | 2                               |
| [N ii] λ6583  | 7429.38                  | 0.03                          | 3.78                                     | 0.12                                          | 265            | 3                               |
| [S ii] λ6716  | 7579.51                  | 0.11                          | 1.14                                     | 0.02                                          | 241            | 9                               |
| [S ii] λ6731  | 7596.16                  | 0.10                          | 1.09                                     | 0.07                                          | 273            | 10                              |

Notes. All uncertainties are the 1σ standard error values. The values stated are calculated for an aperture of 1 arcsec.

Fig. 6. One-dimensional observed optical spectrum of SDSS J134420.86+663717.8 nucleus B in the wavelength range 7000–7700 Å. The observed emission and absorption lines have been marked by vertical red dotted lines and named. The aperture size for spectral extraction is 1 arcsec. The wavelength axis depicts the observed wavelength.

and star-forming galaxies. The curve (Eq. (1)) proposed by Kewley et al. (2001) is called the maximum starburst line and is based on theoretical modelling, while the curve (Eq. (4)) put forth by Kauffmann et al. (2003) is called the pure star-forming line and is based on observational data. If an object falls in the space between these two curves, they are considered to be composite or transitional objects.

\[
\log([\text{O} \text{ iii}] / \text{H} \beta) = 0.61/\log([\text{N} \text{ ii}] / \text{H} \alpha) - 0.05) + 1.3. \quad (4)
\]

To further classify the AGN as Seyferts or LINERS, there are two more curves (Eqs. (5) and (6)). The LINER region can also be populated by regions of shocked gas (Rich et al. 2014).

\[
\log([\text{O} \text{ iii}] / \text{H} \beta) = 1.89 \log([\text{S} \text{ ii}] / \text{H} \alpha) + 0.76. \quad (5)
\]

\[
\log([\text{O} \text{ iii}] / \text{H} \beta) = 1.18 \log([\text{O} \text{ i}] / \text{H} \alpha) + 1.30. \quad (6)
\]

Figure 7 shows the three different plots. We can see from the first plot in Fig. 7 that while both nuclei lie in the composite/transition phase, nucleus A is very close to the AGN part, and nucleus B lies very close to the star forming part of the composite or transition phase. This could be due to the interaction of the galaxies. Interactions of galaxies cause huge amounts of gas and
The rotation curve of a galaxy is the plot of line-of-sight (LOS) velocity against the radial distance from the centre of the galaxy. The rotation curve helps in understanding the distribution of mass as a function of the distance from the centre of the galaxy.

Figure 8 shows the gas rotation curves for the nuclei A and B along the aperture of approximately 8 arcsec on the slit. Additionally, we mark the velocities obtained from our simulation with dashed green lines, to aid in comparing the results of our simulation with the observational data. See Sect. 5.3.2 for more details about the velocity field of the simulated model. It can be seen from the SDSS image of SDSS J134420.86+663717.8 (see Fig. 1) that the galaxies appear to be significantly overlapping. As a result, the extended gas disks associated with the galaxies might overlap in projection. Correspondingly, there is a slight broadening seen in some narrow emission lines, however, no split in profiles is noticed. The rotation curve seems to be divided into three distinct parts. The black dots represent the velocities associated with nucleus A, the red dots represent the velocities associated with nucleus B, while the magenta crosses represent the transition phase between nucleus A and nucleus B. The transition phase is defined as the region between the nuclei along the slit, where the LOS velocity associated with the Hα narrow line increases linearly with spatial distance. The velocities are calculated from the shift of the centre of the Hα narrow line along the slit using the Gaussian fits explained in Sect. 3. In blue, we have overplotted the intensity profile of the Hα narrow line along the slit to provide a better understanding about the nature of the rotation curve. The black dashed line represents the level at which there would be no flux from the Hα line. The zero on the x-axis was arbitrarily selected to coincide with the point on the slit with the highest intensity of the Hα narrow line. The shape of the rotation curve suggests that the galaxies are rotating in opposite directions. This counter-rotation is a feature that can be seen in many cases of interacting galaxies. It arises due to the initial spins of the progenitor galaxies (Barnes 2016). The range of velocities for nucleus A is approximately $\pm 50 \, \text{km} \, \text{s}^{-1}$, while for nucleus B, the range of velocities is approximately $\pm 25 \, \text{km} \, \text{s}^{-1}$. The shape of the rotation curve shows some asymmetry in the case of galaxy A (since we are no longer dealing with just the central arcsec but rather a longer aperture, we refer to the galaxy associated with nucleus A as galaxy A and the galaxy associated with nucleus B as galaxy B). Asymmetry due to interaction with neighbouring galaxies is a well-documented phenomenon (Hodge & Castelaz 2003; Vulcani et al. 2018). Galaxy B has a uniform rotation curve, with no extraordinary features. The transition phase appears to be different from the two other sections, with the LOS velocity increasing almost linearly with spatial distance along the slit. The spatial width of
the transition region is approximately equal to the point source function (PSF) of the telescope, thus, we conclude that the transition region has contribution from both of the nuclei. We note that while the flux from the Hα line is quite low in the region between the two nuclei, it is never zero. The Hα emission line is always present in the transition phase and it is possible to perform Gaussian fitting.

The velocities obtained from the rotation curve can be used to estimate the masses of the central bulges of the galaxies. For this purpose, we used the Baryonic Tully–Fisher relation (BTFR). The original Tully–Fisher relation (Tully & Fisher 1977) is the relation between the luminosity and the rotation velocity of a galaxy, wherein luminosity is considered to be a proxy for total mass of the system. However, luminosity varies with galaxy type, leading to slightly different relations depending on the galaxy being considered. McGaugh et al. (2000), Torres-Flores et al. (2011), McGaugh (2012, and references therein) show that considering baryonic mass, that is, gas mass as well as stellar mass, leads to a more accurate relation between galactic mass and the rotation velocity. We use the maximum velocity obtained from the rotation curve as seen in Fig. 8 to calculate the masses of the bulges in the central 2″. For this purpose, we used the relation stated in Torres-Flores et al. (2011):

\[ M_{\text{bar}} = 10^{9.21 \pm 0.61} V_{\text{max}}^{3.64 \pm 0.28}. \]  

(7)

The relation yields a baryonic bulge mass of approximately 2 × 10^8 \( M_\odot \) for galaxy A and a baryonic bulge mass of approximately 1 × 10^8 \( M_\odot \) for galaxy B. However, we note that the calculated values of the baryonic bulge masses are an underestimate as we cannot be sure if the slit direction probes the major axis of rotation, and considering that the galaxies are interacting, there is a likelihood of perturbation in the velocities, such that the gradient of the velocity lowers. Additionally, nucleus B could have a higher inclination than nucleus A, making it edge-on to our view as compared to nucleus A, which seems to be face-on based on its spectrum. Taking this into consideration, if we divide the value of the baryonic mass of the bulge of galaxy B with the sine value of its inclination, we get approximately equal bulge mass values of 10^8 \( M_\odot \) for both of the galaxies. The value of the inclination is a rough estimate based on the knowledge we have from the observational results and the results of the simulation (see Sect. 5 for a detailed description of the simulation). The inclinations were read off the three dimensional model cube and not taken from the list of simulation parameters. We thus conclude that nucleus A and nucleus B have almost equally massive bulges.

4.3. Mass of the central supermassive black holes

The nuclear spectrum can also be used to calculate the mass of the central supermassive black hole of the galaxy. The mass can be calculated in various ways, depending upon the spectral features available, for example, the virial method (explained in detail in the next subsection), the \( M_{\text{BH}} - \sigma \) relation, the \( M_{\text{BH}} - \sigma^* \) relation, and the \( M_{\text{BH}} - L_{\text{bulge}} \) relation to name a few (Busch 2016, and references therein). In this case, we used the virial method to calculate the mass for nucleus A since we detect broad emission lines, and the \( M_{\text{BH}} - \sigma^* \) relation to calculate the mass for nucleus B, since the spectrum for nucleus B shows stellar absorption lines.

4.3.1. Mass of the black hole for nucleus A

The broad lines in the optical spectrum of nucleus A can be used to calculate the mass of the SMBH at its center. The broad lines arise from the broad line region (BLR) around the central SMBH, where gas rotates at high velocities. Consequently, we can use the virial theorem to derive the mass of the central object.

For the case of AGN with broad lines, Eq. (8) can be used to calculate the mass of the central black hole in the following form (Peterson 2010),

\[ M_{\text{BH}} = \frac{f \Delta V^2 R_{\text{BLR}}}{G}, \]  

(8)

where \( \Delta V \) is the velocity of the broad line region gas, usually characterised by the FWHM or the line dispersion (σ) of the Hβ broad line, \( R_{\text{BLR}} \) is the size of the BLR and \( G \) is the gravitational constant. We used the FWHM values obtained from the Gaussian fit procedure to calculate the mass of the central SMBH. The size of the BLR and the luminosity of the AGN are related to each other by an approximate relation of the form: \( R_{\text{BLR}} \propto L^{1/2} \) (Shields & Peterson 1994). Thus, the luminosity of the AGN continuum can be used to represent the extent of the BLR. The dimensionless factor, “f”, called the virial factor, subsumes within it the effects of everything concerning BLR geometry, its inclination, the kinematics that govern the region, and everything else that is not known to us. The value of “f” is different for every individual AGN but is expected to be of the order of unity. An average value of “f” can be calculated by normalising the AGN \( M_{\text{BH}} - \sigma^* \) relationship to that of quiescent galaxies (Peterson 2010).

Since the Hβ line in our data falls towards the end of the blue spectrum, where the dichroic splits the light into blue and red components, it is better to use the line width and the luminosity
of the Hβ line instead. The relations used to relate the luminosity and the FWHM of the Hα line to the continuum luminosity and the FWHM of the Hβ line are taken from Greene & Ho (2005) and Woo et al. (2015). Finally, the equation used to calculate the mass of the black hole is:

$$M_{\text{BH}} = f \times 10^{6.54 + 0.46 \left( \frac{L_{\text{H}\alpha}}{10^{42} \text{ erg s}^{-1}} \right) 0.06 \left( \frac{\text{FWHM}_{\text{H}\alpha}}{10^3 \text{ km s}^{-1}} \right)} M_{\odot},$$  (9)

The value of $f$ for FWHM-based method was adopted to be 1.12 (Woo et al. 2015). The FWHM of the broad Hα line was taken to be the FWHM of the overall broad component from the Hα + [NII] complex, while the luminosity was calculated as the sum of the luminosities of the two broad components. With the Hubble constant taken to be $H_0 = 69.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$, the mass of the central SMBH is calculated to be approximately $2 \times 10^7 M_{\odot}$. We refrain from stating formal error estimates since the relations we used have intrinsic scatter and the value should be taken to be an order of magnitude estimate.

4.3.2. Mass of the black hole for nucleus B

In the absence of broad line features, the $M_{\text{BH}} - \sigma_*$ relation can be used to estimate the mass of the central black hole of a galaxy, where $\sigma_*$ is the stellar velocity dispersion of the galactic bulge. The $M_{\text{BH}} - \sigma_*$ relation, called the Faber Jackson law for black holes (Merritt 2000), has undergone several changes over the years with regards to the power of $\sigma_*$. The relation used here was put forth by McConnell et al. (2011) and takes the form:

$$M_{\text{BH}} \approx 1.9 \left( \frac{\sigma_*}{200 \text{ km s}^{-1}} \right)^{2.1} 10^8 M_{\odot},$$  (10)

The stellar velocity dispersion of the galaxy was found by fitting a stellar template to the optical spectrum of the galaxy using the pPXF package (version v6.7.6), developed by Michele Cappellari (Cappellari 2017; Cappellari & Emsellem 2004). The pPXF package can fit a large set of stellar templates without encountering a template mismatch due to different ranges of wavelength. We used the stellar spectra from the MILES library (Vazdekis et al. 2010) to fit the stellar template to our data. The MILES library consists of synthetic single-age, single-metallicity stellar populations over the full optical spectral range. The value of $\sigma_*$ obtained from the fitting was $139 \pm 32 \text{ km s}^{-1}$. Plugging this in Eq. (10), the mass of the black hole for nucleus B is calculated to be approximately $3 \times 10^7 M_{\odot}$. As with nucleus A, the value for the mass of the central SMBH should be taken as an order of magnitude estimate since the relations we use have intrinsic scatter which deters us from making a formal error estimation.

4.4. Masses of the galaxies

Finally, we used mass to light ratio to estimate the masses of the individual galaxies. To do this, we used an average mass to light ratio of $\sim 200 h M_{\odot}/L_{\odot}$ from Gonzalez et al. (2019), for close galaxy pairs in the optical regime. We used the continuum luminosities calculated at various distances from the centre to fit Sersic profiles for both of the galaxies, and used these to get integrated values of the luminosities of the entire galaxies. Then we plugged this value of luminosity in the mass to light ratio to estimate the mass of the galaxy. We excluded the central arcsec while fitting the Sersic profile in order to disconsider the contribution from the centre of the galaxy. This yielded values of approximately $2 \times 10^{12} M_{\odot}$ for galaxy A and approximately $6 \times 10^{11} M_{\odot}$ for galaxy B. These values seem to be in agreement with the general galaxy mass estimates. However, we note that as the galaxies are interacting with each other, there must be intermixing of gas, which is not properly accounted for here. This can lead to an overestimation or underestimation of mass as we cannot be sure whether the contribution to luminosity at any particular point comes from one or two galaxies. Consequently, the values of mass quoted here should be taken as order of magnitude estimates.

5. Simulation

While we could ascertain some of the properties of the galaxies from the data available to us, it is interesting to understand the initial conditions of the participant galaxies. For this, simulations play a big role in increasing our understanding. The current morphology of the system provides an inkling regarding the angles at which the galaxies might have approached each other. We must keep in mind, though, that since what we see is the two-dimensional projection of the three-dimensional morphology on the plane of the sky, one projection might be explained by many different 3D models. Projection effects could cause tidal tails to cross and might lead to association with the “incorrect” galaxy, for example. Antennae galaxies have crossing tidal tails. Additionally, one model might be used to explain different structures by introducing different viewing angles, for example, Scharwächter et al. (2004) report a multi-particle model for the QSO 3C48 with conditions similar to those used to interpret the appearance of the Antennae galaxies but with a different viewing angle. Our aim in building the simulation is to model a spatial and kinematical look-alike of SDSS J134420.86+663717.8, and shed some light on one of the possible sets of initial conditions.

5.1. Basis of our simulation

A visual inspection of the image of the object while keeping in mind the properties determined from the analysis in Sect. 4 supplied a vague idea regarding the initial conditions. The galaxies are at different redshifts and have almost equally massive central SMBHs. The tidal tail of the galaxy at higher redshift appears elongated and extended, while the tidal tail of the galaxy at lower redshift appears to be foreshortened in comparison. The foreshortening might be a result of the viewing angle being such that we look at the tidal tail edge-on. With this in mind, we looked at a model of interacting galaxies presented by Barnes & Hernquist (1996, 1998). They presented eight different sets of encounter parameters and studied the outcomes for the case of two equal mass galaxies.

The models consisted of three types of matter, namely stars, dark matter, and interstellar gas. Barnes & Hernquist (1996) assumed that the stars and the dark matter could be described by the collisionless Boltzmann equation, whereas the gas was modelled by the standard laws for a compressible fluid along with gravitational forces, radiative cooling, and shock heating. Poisson’s equation was used to obtain the gravitational field generated by the stars, dark matter, and gas. The bulge to disk mass ratio was taken to be 1:3:16, with the gas contributing 10% of the disk mass. We focused on one of the eight scenarios presented in Barnes & Hernquist (1996): encounter A, as, coincidentally, the outcome of this scenario resembles SDSS J134420.86+663717.8 most closely.

The parameters for this parabolic encounter are: pericentric separation $R_0 = 0.2$, $i_1 = 71$, $\omega_1 = 30$, $i_2 = 0$, $\omega_2 = 0$, and
total number of particles \( N = 10, 112 \). The parameters, “\( i \)” and “\( \omega \)”, describe the inclination of the orbit to the spin plane of the galaxy, and the angle between the node and the point of closest approach to the center of the disk without being disrupted, respectively, as defined and used by Toomre & Toomre (1972). They used a length unit of 40 kpc and a time unit of 250 Myr. The paper (Barnes & Hernquist 1996) shows pictorial representations of the objects at various time steps and explains each step in careful detail. Figure 9 shows their simulated result that resembles SDSS J134420.86+663717.8 most closely. A comparison with Fig. 1 reveals striking similarities in their morphology. However, there was still some difference in the morphology of the Barnes and Hernquist Model (hereafter referred to as the B&H Model) and the SDSS image, for example, the line connecting the two nuclei in the B&H Model should have a slight tilt to resemble the SDSS image, the tip of the tidal tail associated with nucleus B, which is the nucleus to the left in the image above. Credit: (Barnes & Hernquist 1996).

Fig. 9. Simulated SDSS J134420.86+663717.8 look-alike \( \approx 375 \) Myr after the first collision. Comparison with Fig. 1 shows striking similarities between SDSS J134420.86+663717.8 and the model. Two distinct nuclei are visible, along with the extensive tidal tail associated with nucleus B, which is the nucleus to the left in the image above. Credit: (Barnes & Hernquist 1996).

but in order to obtain more detailed knowledge of the orbital elements and the orientation of the hosts, we employed \( N \)-body calculations. A predictor-corrector method was used and implemented based on the description of the code and the algorithms in Aarseth (2003).

5.2.1. Method

If we consider particles to be subject to gravitational forces only, the forces would vary smoothly with respect to time. In such a case, a polynomial fit could be applied to the force (or acceleration), and force at time \( t_0 + \Delta t \) could be predicted via extrapolation. \( N \)-body simulations have been used to study a wide range of problems, for example: tidal disruptions of dwarf spheroid galaxies orbiting the Milky Way (Oh et al. 1995).

Instead of initialising each point individually, we used twelve parameters to set the starting conditions of the system: accuracy parameter \( \eta \), softening parameter or Plummer constant \( \epsilon \), number of galaxies, number of particles \( N \), outer radius, central mass, galactic mass ratios, velocity factors, rotations, translations, velocity transformations, and the output time step. The initial structure of our galaxies was that of two disc galaxies, with an outer disc which has the same mass as the central bulge. We set the number of particles \( N \), number of rings, a radius of the outer ring, and a mass of the entire galaxy to generate our galaxy-like structure. For this case, we used an outer radius of 30 kpc, with twenty particles in the outer ring and ten particles in the inner ring, and an additional particle as the galactic centre, that is, bulge, molecular zone, and inner portion of the disc. The outer particles were spaced equally in an outer ring of radius \( R = 30 \) kpc, while the ten inner particles were spaced equally in an inner ring at radius 15 kpc, such that all particles had the same arc length separation to their respective “left” and “right” neighbours. The mass of the central particle was taken to be \( 10^8 M_\odot \) and is equal to the mass of all other particles. We do not explicitly consider a description of an extended mass distribution at the centre, like a bulge or a central molecular zone, due to the small number of particles, but approximate the mass distribution of the cloud through our central particle. This assumption, therefore, does not contradict our bulge mass estimates of approximately \( 10^8 M_\odot \) for both of the galaxies, since the bulge mass values were derived for the central 2", while the central particle here spans approximately 5" in diameter. The values of the galaxy masses are in good agreement with the values obtained dynamically in Sect. 4.4. We initialised the galaxies with velocities of \( 50 \) pc Myr\(^{-1} \) for the blue (galaxy A) galaxy and \(-125 \) pc Myr\(^{-1} \) for the red (galaxy B) galaxy. We chose these values based on the velocity difference calculated from the rotation curve. However, we also tried larger and smaller values for the velocities of both galaxies in various combinations and concluded that the velocity values obtained from the observed data yield the most “lookalike” results, spatially. Table 4 lists the starting parameters used to implement the simulation.

5.2.2. Limitations

The major limitation of our code is the rather small number of particles used to define our galaxies. However, we note that the total number of particles considered by us (\( 3 < N_{\text{total}} < 100 \)) is within the range of “typical particle number for applications” specified in Aarseth (2003). We will now present two different factors to demonstrate the accuracy of our results, that is, conservation of energy and stability of a galaxy without tidal forces.

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with three different characteristic times: \( t_{\text{start}} \), time at which we initialise the system, \( t_{\text{symmetry}} \): time at which the galaxy first loses its initial structure, and \( t_{\text{chaos}} \): time at which the galaxy first loses its symmetry. After \( t_{\text{chaos}} \) we cannot be certain that the galactic superstructures are caused by only tidal forces, they could as well be caused by the chaotic motion of the galaxies themselves. We refrain from crossing \( t_{\text{chaos}} \) (\( t_{\text{chaos}} = 2500 \) Myr in our case) in our analysis to guarantee the integrity of our results. Beyond \( t_{\text{chaos}} \), the system loses symmetry.

Going back to the former point concerning the conservation of energy, we consider the total energy of the system for the duration of the simulation. Figure 10 shows the time evolution of the energy of a single stable galaxy. There is a significant loss in accuracy after 3000 Myr. We do not consider any values beyond this time for our merger simulation, as we consider this point to be an absolute break-down for the accuracy of our simulation. For \( t < 3000 \) Myr, the maximum energy change is \( 1.81 \times 10^{-6}\% \). We can compare this to the maximum energy change before \( t_{\text{chaos}} \) which is \( 1.22 \times 10^{-11}\% \). In our analysis we never surpass \( t_{\text{chaos}} \).

5.3. Visualisation

Here, we show how the imaging and spectroscopy we present for this galaxy merger is matched by the simulations we performed.

5.3.1. Visualising the results from the simulation

In order to get a clear view of the distribution of matter predicted by the simulations and to have a higher degree of confidence regarding the structures involved, we run the simulation 15 times (each with 62 particles with 31 particles per galaxy) with minimal alterations to the starting conditions and overlap the resulting data to produce a single image with a total of 930 plotted points such that none of the single particles is of any particular interest.

To provide small alterations to the initial conditions, we rotate the galaxies around their rotation axis by small angles (five increments of \( \pi/50 \) each), and use three different radii (radial factors of 0.97, 1.00, and 1.03) for each of these five systems. We rotate the 3D Model that we get as the result of the simulation and flatten it so that we can view it at an angle which makes the system comparable to our view of SDSS J134420.86+663717.8. To estimate the inclinations of the galaxies in the result of the simulation, we rotate the Model by \( 90^\circ \) around the \( z \)-axis, and then rotate it around the \( y \)-axis, such that the line of nodes is along the new line-of-sight (see Fig. A.1). The rotated cube has an orientation such that it shows the planes of the galaxies to be almost orthogonal not only to each other but also to the new line-of-sight. This allows us to roughly estimate the inclination angles by looking at the original line of sight and the planes of the two galaxies. They are approximately \( 10^\circ \) for the red galaxy and approximately \( 90^\circ \) for the blue galaxy.

5.3.2. The predicted velocity field

Figure 11a shows the two-dimensional projection of the Model and Fig. 11b shows the SDSS image of the galaxies. The comparison shows good similarities between them. The blue-coloured tail resembles the foreshortened tail associated with galaxy A to the south-west in the SDSS image, while the red-coloured tail looks like the arching tidal tail associated with galaxy B to the north-east in the SDSS image. The blue tail loops around the nucleus of the blue galaxy A in the model. The red tail seems to be foreshortened. Moreover, the distance between the nuclei also seems to be similar for both of the images – the simulation result and the data. Additionally, in Fig. 11c we show the radial velocities predicted by our model. The north-western tidal arm seems to have a rather uniform velocity distribution of around \( \pm 60 \) km s\(^{-1}\), while the region where the tail meets the galaxy B body has velocity of \( \pm 40 \) km s\(^{-1}\). The velocity rises in the main body of galaxy B, such that the nuclear region of galaxy B appears to have a velocity of around \( 180 \) km s\(^{-1}\) as expected from the line-of-sight velocity plot in Fig. 8. From Fig. 11a, we see that the southern part of the structure has a mixture of particles from both of the galaxies, such that the (blue) particles belonging to galaxy A are enveloped on the east and the west by the (red) particles belonging to galaxy B. This is reflected in the velocity map in Fig. 11c, as well. We see an envelope of approximately

| Variable | Value | Units |
|----------|-------|-------|
| Number of galaxies | 2 | n.a |
| \( N \) | [20,10] | n.a |
| Outer radius | 3.0 | kpc |
| Central mass | \( 10^{11} \) | \( M_\odot \) |
| Galaxy mass ratios | [1, 1] | n.a |
| Rotations around \( x \)-axis | \([-17\pi/36, \pi/18]\) | radians |
| Rotations around \( y \)-axis | [0, 0] | radians |
| Rotations around \( z \)-axis | \([-\pi/18, \pi/18]\) | radians |
| Galaxy 1 velocity factors | [1.32, 1.03] | n.a |
| Galaxy 2 velocity factors | [1.32, 1.03] | n.a |
| Galaxy 1 translation | \([-30, -25, 0]\) | kpc |
| Galaxy 2 translation | \([+30, +25, 0]\) | kpc |
| Galaxy 1 group velocity | \([50, 5, 1]\) | pc Myr\(^{-1}\) |
| Galaxy 2 group velocity | \([-125, -5, -1]\) | pc Myr\(^{-1}\) |
The velocities of the nuclear regions obtained from the model agree with the values estimated from the rotation curve in Fig. 8.

5.3.3. Three dimensional projection

Figure 12 shows the three-dimensional projection of the simulated data. The 3D cube has been rotated so that the difference in the morphology of the galaxies based on the viewing angle is apparent. In Fig. 12a we show, for completeness, the scenario as seen by the observer in the sky. Galaxy A (blue) to the south-west and galaxy B (red) to the north-east. In Figs. 12b–d, we show, successively, the view from directions in which either one or both the galaxies are seen edge on. We note that the galaxies remain orthogonal to each other even while interacting.

From Fig. 12c, we see the blue-coloured system A almost face on. It is evident that the distribution of matter is highly asymmetric, and that the nucleus and a larger mass agglomeration lie almost on opposite sides of a ring-like structure. This corresponds to the images in Fig. 11, and in particular in the velocity map in Fig. 11c, to the nuclear region of galaxy A and to the very blue-shifted region of that system south of the nucleus A that coincides with the mass agglomeration in the south visible in the top and middle image in Figs. 11a and b.

For the red-coloured system B we also find a highly asymmetric distribution of matter. This system can be seen almost face on in Fig. 12b. Here, we have the well pronounced tidal arm to the north and the nuclear region of the B system that is attached to it. At larger distances from the nucleus B, we find highly disturbed matter associations that are offset in velocity from the tidal arm and the nucleus, and that have partially been lifted out of the red galactic disk (see also Fig. 12d). Hence, we can understand why in the velocity map in Fig. 11c, the highly blue-shifted part of galaxy A, showing extremely negative values of velocities, is embedded in the very extended matter from the B galaxy system, showing redshifted velocities mostly between $-40 \text{ km s}^{-1}$ and $40 \text{ km s}^{-1}$.

The striking similarities between the model and the actual galaxies show that we are on the right path, and SDSS J134420.86+663717.8 could indeed be a product of an orthogonal interaction between two spiral galaxies.

6. Conclusions and summary

We present the optical long-slit spectroscopic data of SDSS J134420.86+663717.8, a pair of interacting galaxies. We study their optical spectra and analyse the nature of the two galaxies that form the object. Using diagnostic diagrams and based on the presence of broad hydrogen recombination lines, we conclude that the mechanism responsible for emission in the host of nucleus A is AGN-like, with Seyfert 1 properties, whereas nucleus B appears to be star-forming in nature. There appear to be two broad components for the hydrogen recombination lines. This hints at a structure in the broad line region. There are almost equally massive SMBH at the centres of both host galaxies, with masses of a few times $10^7 \, M_\odot$. The Hα rotation curve of galaxy A shows some asymmetry, while the rotation curve of galaxy B appears to be uniform. There is a transition phase in the Hα rotation curve which appears to be different from the rotation curves corresponding to galaxies A and B. We attribute this to contributions from both of the galaxies. Additionally, we use a simple $N$-body simulation to understand the possible initial conditions of SDSS J134420.86+663717.8. With initial parameters of $R_0 = 22.5 \, \text{kpc}$, $i_1 = -85^\circ$, $\omega_1 = -10^\circ$, $i_2 = 10^\circ$, and $\omega_2 = 0^\circ$, the outcome of the simulation resembles our object rather closely. We thus conclude that
SDSS J134420.86+663717.8 is an ongoing merger of two almost orthogonal spiral galaxies with approximately equal masses. The galaxies appear to remain orthogonal during the process of interaction.

With almost equally massive hosts, SDSS J134420.86+663717.8 constitutes a major merger. Major mergers are interesting as they can induce bursts of star-formation and feed the central SMBH, thus triggering an AGN phase (Casteels et al. 2014, and references therein). This appears to be true in the case of SDSS J134420.86+663717.8. Nucleus A displays AGN behavior and has broad emission lines. Ellison et al. (2019) conclude that there is a connection between AGN triggering and merging at low $z$ ($<1$) for optical and mid-IR selected AGN. SDSS J134420.86+663717.8 seems to conform to this conclusion, although, as it is a single case, it cannot be used to support or contradict the general theories pertaining to the evolution of galaxies via mergers or interaction. Additionally, it is difficult to make a general statement for all AGN due to contradictory studies (e.g., Keel et al. 1985; Bessiere et al. 2012; Satyapal et al. 2014; Goulding et al. 2018, against: Gabor et al. 2009; Mechtley et al. 2016; Marian et al. 2019). This requires a sample chosen based on similar criteria over the electromagnetic range.

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Appendix A: Estimation of the inclinations of galaxies

Fig. A.1. 3D model obtained as the result of the simulation is rotated by 90° around the xy-plane, and then rotated about the z-axis such that the line of nodes is the new line of sight for us. The black arrow labelled “Line of sight” shows the orientation of the plane containing the original line of sight. It can be seen that the galaxies are mutually orthogonal to each other. Additionally, the red galaxy lies along the plane of sight, while the blue galaxy is perpendicular to it.