3D spectroscopy of merger Seyfert galaxy Mrk 334: nuclear starburst, superwind and the circumnuclear cavern

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ABSTRACT

We are presenting new results on kinematics and structure of the Mrk 334 Seyfert galaxy. Panoramic (3D) spectroscopy is performed at the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences using the integral-field Multi-Pupil Fiber Spectrograph (MPFS) and scanning Fabry–Pérot interferometer. The deep images have revealed that Mrk 334 is observed during the final stage of its merging with a massive companion. A possible mass ratio ranges from 1/5 to 1/3. The merger has triggered mass redistribution in the disc resulting in an intensification of nuclear activity and in a burst of star formation in the inner region of the galaxy. The circumnuclear starburst is so intense that its contribution to the gas ionization exceeds that contribution of the active galactic nuclei (AGN). We interpret the nuclear gas outflow with velocities of \( \sim 200 \text{ km s}^{-1} \) as a galactic superwind that accompanies the violent star formation. This suggestion is consistent with the asymmetric X-ray brightness distribution in Mrk 334. The trajectory of the fragments of the disrupted satellite in the vicinity of the main galaxy nucleus can be traced. In the galaxy disc, a cavern is found that is filled with a low-density ionized gas. We consider this region to be the place where the remnants of the companion have recently penetrated through the gaseous disc of the main galaxy.

Key words: galaxies: individual: Mrk 334 – galaxies: interactions – galaxies: kinematics and dynamics – galaxies: Seyfert – galaxies: starburst.

1 INTRODUCTION

Numerical simulations demonstrate that galaxy interaction stimulates a concentration of gas in its central regions, thereby triggering nuclear activity and/or a burst of star formation (Barnes & Hernquist 1991; Springel, Di Matteo & Hernquist 2005; Bekki, Shioya & Whiting 2006). Many authors have tried to find a correlation between an active galactic nucleus (AGN) phenomenon and galaxy environment: the presence of companions or traces of interaction (Dahari 1985; De Robertis, Yee & Hayhoe 1998; Schmitt 2001; Knapen 2005). However, statistically significant correlation has not been found.

A number of authors suggest that the activity may be triggered and sustained by a complex mechanism that includes several factors (see Martini 2004, and the references therein). It is clear that only a detailed analysis of the kinematics and dynamics of both the inner (100–1000 pc scale) and outer regions in active galaxies would make it possible to understand how in each particular case the ‘fuel’ (interstellar gas) is brought into the domain of action of the gravitational forces of the AGN ‘central engine’.

This paper continues a series of papers dedicated to a detailed study of the inner kinematics of active galaxies via methods of panoramic (3D) spectroscopy. This technique provides spectra for every spatial element (‘spaxel’) of a two-dimensional (2D) field of view. It is a powerful tool for studying non-circular motions and gas ionization properties both in the circumnuclear and external regions. Our work is aimed to investigate the relation between the gas kinematics, morphological features and nuclear activity in individual galaxies as well as the mechanisms of the central region feeding. We have already published the results concerning Mrk 315 (Ciroi et al. 2005), NGC 6104 (Smirnova, Moiseev & Afanasiev 2006) and Mrk 533 (Smirnova et al. 2007). In this paper, we report a detailed study of Mrk 334.

Mrk 334 (VV 806, UGC 6) is a peculiar galaxy with Sy I.8 nucleus (according to the NED data base). This object has been popular among the researchers due to its peculiar appearance on optical images: it has an asymmetric eastward-extending arm (V orontsov-Vel’yaminov 1977) and a bright H\( \alpha \) condensation near the nucleus (Gonzalez Delgado et al. 1997). The latter authors suggested that the object actually consisted of two merging galaxies. Mrk 334 is notable for violent star formation, resulting in high IR luminosity \( L_{\text{IR}} = 8.9 \times 10^{11} L_\odot \) (Pérez García & Rodríguez Espinosa 2001). Rothberg & Joseph (2004) classify it as a luminous infrared galaxy.

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(LIRG). Maiolino et al. (1997) suggested that the peculiarities in the structure of the galaxy are indicative of its recent interaction with a companion, which has triggered the nuclear activity. However, when and what did the galaxy interact with? In the present paper, we try to answer this question and to look for the feedback effects between the central and surrounding regions.

The paper has the following layout. Section 2 describes the observations and the data reduction; Section 3 analyses the distribution of ionized gas and stars both in the inner disc and in the outer regions of the galaxy. Section 4 analyses the ionization state of selected regions in Mrk 334, and in Section 5 the kinematics of the gas and stars are considered. Section 6 studies the peculiarities of X-ray radiation according to the ROSAT data, and Section 7 includes an overall discussion of the whole galaxy structure and the circumnuclear ionized gas cavern.

The adopted distance to the galaxy – 91.4 Mpc (Maiolino et al. 1997) – corresponds to a scale of 443 pc arcsec⁻¹ (for redshift z = 0.022 and H₀ = 75 km s⁻¹ Mpc⁻¹).

2 OBSERVATIONS AND DATA REDUCTION

All observations were made in the prime focus of the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS). Table 1 provides the log of the observations. The central region of Mrk 334 was observed with the Multi-Pupil Fiber Spectrograph (MPFS). The large-scale kinematics and galactic environment were studied using the SCORPIO multimode focal reducer operating in the modes of scanning Fabry–Pérot interferometer (FPI) and broad-band imaging. The detectors used in 2006 and 2002 were a CCD EEV42-40 (2048 × 2048 pixels) and a CCD TK1024 (1024 × 1024 pixels), correspondingly.

2.1 MPFS integral-field spectrograph

The integral-field spectrograph MPFS (Afanasiev, Dodonov & Moiseev 2001) takes simultaneous spectra of 256 spatial elements arranged in the form of 16 × 16 square lenses array with a scale of 1 arcsec per spaxel. Behind each lens an optical fibre is located whose other end is packed into the spectrograph slit. The sky background spectrum was simultaneously taken with 17 additional fibres located 4 arcmin away from the object. The wavelength interval included numerous emission lines of ionized gas and absorption features of the stellar population.

The preliminary data reduction steps were described earlier (Moiseev, Valdés & Chavushyan 2004; Smirnova et al. 2007). Reduction yields a ‘data cube’, where each pixel in the 16 × 16 arcsec² field has a spectrum associated with it. The spectra of the spectrophotometric standard stars were used to convert counts into absolute fluxes. Observations were made successively in two spectral intervals (see Table 1). The overlap of the two spectral domains allowed us to join them so as to operate with a single data cube covering a λλ3740–7220 Å spectral range.

To construct the stellar velocity field, we use the cross-correlation technique adapted for MPFS data (Moiseev 2001). Spectra from MILES library (Sánchez-Blázquez et al. 2006) smoothed to the instrumental resolution were adapted as templates for cross-correlation. We have mapped the line-of-sight velocity and brightness distribution fields for the main emission lines using the Gaussian fitting of their profiles. Underlying absorption lines were taken in account as approximation by a linear combination of smoothed and redshifted MILES templates.

2.2 SCORPIO

SCORPIO universal instrument (Afanasiev & Moiseev 2005) allows various spectroscopic and photometric observations to be performed within 6 arcmin field of view. Below we describe each of the modes employed in detail.

2.2.1 Fabry–Pérot interferometer

We used the scanning FPI operating in the Hα emission line to study the kinematics of the ionized gas. During the observations, we successively took 32 interference images of the object by changing the FPI plate gap. A detailed description of the technique of observations and data reduction can be found in the papers by Moiseev (2002) and Moiseev & Egorov (2008). This reduction yields a data cube, where a 32-channel spectrum with a sampling step of 0.9 Å is attached to each 0.28 arcsec pixel. The spectroscopic resolution is 2.8 Å. The velocity field of the ionized gas and images in the Hα emission line were mapped using Gaussian fitting of the emission-line profiles. We also generated an image of the galaxy in the continuum close to the emission line.

We calibrated the emission-line flux map into absolute energy units (erg s⁻¹ cm⁻²) by comparing it with the Hα distribution according to the MPFS data for the central region. The total Hα-luminosity of the galaxy was found to be 2.3 × 10⁴¹ erg s⁻¹ given the adopted extinction of A_K = 1.5 mag. The extinction estimate is based on the Hα/Hβ line intensity ratio for the H II region to the west of the nucleus (hereinafter referred to as ‘Region A’). According to Kennicutt (1998a), such a luminosity corresponds to star formation rate (SFR) of 18 M⊙ yr⁻¹, if we neglect a contribution from the AGN in the Hα flux.

2.2.2 Direct images

We took images of the galaxy in the Johnson–Cousins V and R bands with a sampling of 0.35 arcsec per pixel. Non-photometric

Table 1. Log of the observations.

| Date            | Instrument | Exp. time (s) | Sp. range | Sp. resol. | Seeing (arcsec) |
|-----------------|------------|---------------|-----------|------------|-----------------|
| 2006 November 23 | MPFS       | 7200          | 3740–5850 Å | 6.5 Å      | 1.4             |
|                 |            | 7200          | 4300–7220 Å | 6.5 Å      | 1.4             |
| 2002 September 05 | SCORPIO   | 6400          | Hα        | 2.8 Å      | 1.3             |
| (FPI)           |            |               |           |            |                 |
| 2006 October 23 | SCORPIO   | 660           | V         | 1.4        |                 |
| (Images)        |            | 1020          | R         | 1.4        |                 |
weather conditions prevented the use of standard stars to calibrate fluxes. We performed a coarse calibration in the V band based on the aperture photometry data listed in the HyperLeda data base (http://leda.univ-lyon1.fr/). An accuracy of the zero-point is 0.1–0.2 mag. We calibrated the R image assuming that the average colour index in the disc of Mrk 334 corresponds to that of a normal Sb-Sc-type galaxy: \((V - R) \approx 0.5\). The assumption of the normal \(V - R\) colour is justified by the known normal two Micron All Sky Survey (2MASS) infrared colours of Mrk 334. The depth of the surface brightness measurements reaches 25.5 mag arcsec\(^{-2}\) in the \(V\) and \(R\) bands, which is significantly deeper than the other known images of Mrk 334.

### 3 MORPHOLOGICAL FEATURES OF MRK 334

#### 3.1 Line and continuum images

We use the MPFS spectra to construct the maps in various emission lines covering the \(7 \times 7\) kpc\(^2\) central region of Mrk 334 (see Fig. 1). The maps show some other bright regions besides the nucleus. The brightest of them, the Region ‘A’, is located 4 arcsec to the west of the nucleus. Gonzalez Delgado et al. (1997) were the first to find it in Hz. At our maps it can be seen in other emission lines and in the continuum. Fainter Region ‘B’ is located \(r = 3–4\) arcsec to the south of the nucleus and shows up mostly only in the \([\text{O} \text{II}]\lambda\lambda 4959, 5007\) doublet. The continuum image exhibits, in addition to Region ‘A’, an amorphous structure that we refer to as Region ‘C’.

Many authors (see Introduction) believed Mrk 334 to be an interacting system. Their conclusion was based mostly on the presence of an asymmetric spiral arm to the east of the nucleus resembling a tidal tail (Hunt et al. 1997; Rothberg & Joseph 2004). This feature is clearly visible on the FPI continuum image and is absent in the Hz line map (Fig. 2). Therefore, this arm does not harbour star-forming regions.

#### 3.2 Multicomponent structure of the disc and outer filaments

The deep images of the galaxy show that the tidal arm noted above is the brightest part of the vast system of shells and lower surface brightness filaments (Fig. 3). The shells have sharp outer edges located about 70 arcsec north-west and about 100 arcsec south-west of the nucleus, which corresponds to 31 and 44 kpc, respectively. The \(R\)-band surface brightness of the outer regions is about 24–25 mag arcsec\(^{-2}\). Similar arc-like features are typical of galaxies currently interacting or having interacted in the past with a companion (Schweizer & Seitzer 1988; Wehner & Gallagher 2005).

To study the brightness distribution in the filaments, we must remove the axisymmetric components of the galaxy – the bulge and the disc. To decompose the image into components, we use an iterative method of constructing 1D and 2D models (Moiseev et al. 2004; Cirol et al. 2005). The idea of the method is to determine the parameters of the exponential disc from the outer parts of the azimuthally averaged brightness profile and subtract the resulting brightness distribution from the original image. The residual image is averaged over round apertures and fitted to the Sérsic’s profile for the bulge. We then subtract the bulge model from the initial image and use the residual image to build the next iteration for the disc. When constructing the model we masked the high-contrast features like stars and tidal spirals. We found the galaxy image to be best approximated by the model consisting of a bulge and two exponential discs with different radial scales. Table 2 lists the parameters of the photometric components. Here \(n\), \(r_e\), and \(\mu_{eff}\) are the exponent, effective radius and brightness of the bulge, respectively, and \(\mu_c\) and \(h\) are the central surface brightness and radial disc scalelength. The position angle and the apparent ellipticity of the discs were fixed in accordance with the orientation of the ionized-gas disc (Section 5).

The results of decomposition performed in the two filters agree fairly well with each other, except that the scalelength of the outer disc is larger by a factor of 1.3 in the \(R\) band.

Fig. 4 shows the surface-brightness profile computed by averaging the brightness over elliptical rings. It shows a well-defined break at \(r = 50–60\) arcsec and is dominated by the outer disc at larger galactocentric distances. Such multicomponent (two-tiered) discs have now become increasingly popular among the researchers. According to the classification proposed by Erwin, Beckman & Pohlen (2005), Mrk 334 exhibits a typical type III (antitruncated) surface-brightness profile. Among the galaxies studied by Erwin et al. (2005), such profile characterizes mostly post-interacting objects. A detailed study of individual galaxies also suggests that interaction events may result in the formation of multiterrified discs. Examples include NGC 615 (Sil’chenko, Vlasyuk & Alvarado 2001), Mrk 315 (Cirol et al. 2005), NGC 7217 and NGC 7742 (Sil’chenko & Moiseev 2006).

Mrk 334 appears to represent configuration, where the debris of the companion torn apart by the tidal forces precess in the plane of the galaxy. The outer disc is being formed right now with a relatively long scalelength and a low central brightness. Indeed the parameters of the inner disc (Table 2) are typical for a spiral galaxy, whereas the outer disc has a rather long radial scalelength and the \(\mu_0\) that is typical for low surface brightness (LSB) galaxies. In Mrk334, we caught an LSB disc in the process of formation. Here, the mean brightness profile has already become close to an exponential, despite the asymmetry of azimuthal light distribution that is still very inhomogeneous. The brightness of the outer disc should become more homogeneous after a few revolutions that is after about 0.5–1 Gyr.
Fig. 2. FPI images of Mrk 334 in the Hα line (a) and in the continuum (b). The square indicates the region observed with the MPFS.

Fig. 3. R-band image of the galaxy taken with the 6-m telescope (a) and a residual image after the subtraction of the 2D model (b). The scale is in mag arcsec$^{-2}$.

Table 2. Parameters of the photometric decomposition.

| Component       | Parameter | $V$ filter | $R$ filter |
|-----------------|-----------|------------|------------|
| Sersic's bulge  | n         | 2          | 2          |
|                 | $\mu_{\text{eff}}$ | 20.3 mag   | 19.8 mag   |
|                 | $r_0$     | 3.2 arcsec (1.4 kpc) | 3.2 arcsec (1.4 kpc) |
| Inner disc      | $\mu_0$  | 21.5 mag   | 20.9 mag   |
|                 | $h$       | 7.8 arcsec (3.5 kpc) | 8.7 arcsec (3.9 kpc) |
| Outer disc      | $\mu_0$  | 24.8 mag   | 24.2 mag   |
|                 | $h$       | 32 arcsec (14 kpc) | 43 arcsec (19 kpc) |

Fig. 3(b) shows the $R$-band brightness distribution after subtracting the model consisting of two discs and a bulge. A complex system of bright loops becomes immediately visible. Three characteristic radial scales can be identified: the circumnuclear ring with a radius of about 4–5 kpc; inner filaments at a distance of $r = 9–13$ kpc; and outer features – a loop and an arc located north-west and south-west of the nucleus, respectively, which can be observed beyond $r \sim 40$ kpc. This subdivision of tidal features is rather arbitrary. We are most probably observing a disruption of a single galaxy torn apart by tidal forces and spread along its orbit around Mrk 334. The bulk of the companion stars is concentrated in the central region, because the mean brightness of the inner and circumnuclear filaments is twice higher than that of the outer ones.

The total luminosity contribution of all inner and outer filaments determined after subtracting the 2D model is 30 per cent in the $V$ band and 25 per cent in the $R$ band. Under the assumption that all filaments (including the circumnuclear ones) were formed by stars of the satellite, we have derived the mass ratio for the galaxies before interaction ranging from 1/5 to 1/3 for the equal $M/L$ ratios in both galaxies. The scatter of the estimates is mostly due
3D spectroscopy of Mrk 334

Figure 5. The distribution of the \((V - R)\) colour index in the inner regions of the galaxy (a); residual brightness distribution for the same region (b), and the \textit{HST}/WFPC2 archive image in the F606W filter (c). The contours in figures (b) and (c) show the boundaries of the condensations identified via MPFS observations.

Figure 6. Integrated spectra of individual regions in Mrk 334.

to the uncertain fraction of companion stars dropped into the outer disc. This ratio is close to the conventional boundary between minor and major merging. Whereas in the former case the interaction should rather be regarded as a simple accretion of a low-mass companion by the primary galaxy, in the case of major merging this process also distorts appreciably the structure of the more massive companion.

Fig. 5 shows the central part of Mrk 334. The system of arcs and loops corresponding to the orbit of the disrupted companion shows up conspicuously on the map of residual brightness. According to the \((V - R)\) maps, individual fragments of these loops stand out because of their bluer colours, which are indicative of the presence of younger population that may have formed in the process of interaction between the galaxies. The red colour of Region ‘A’ is evidently due to the \(\text{H}\alpha\) emission falls within the \(R\)-filter passband. Note that the tidal structures at \(r = 5–10\) arcsec are most likely located outside the plane of the galaxy, as follows from the analysis of the gas velocity field (Section 5).

At the same time, the circumnuclear spiral at \(r < 5\) arcsec, which shows up on \textit{Hubble Space Telescope (HST)} images (Fig. 5c) seems to belong to the galaxy disc plane. The authors having reported \textit{HST} images of Mrk 334 (Martini & Pogge 1999; Martini et al. 2001) have also pointed out the minispiral and chaotic dust features in the circumnuclear region.

4 SOURCES OF GAS IONIZATION

Fig. 6 shows the integrated spectra of Regions ‘A’, ‘B’ and ‘C’ and of the nucleus extracted from the MPFS data cube. The boundaries of these regions are shown in Fig. 5. The spectra of the nucleus and of the knot ‘A’ have much in common: both exhibit strong Balmer lines and weaker forbidden lines, mostly \([\text{O}\,\text{iii}]\lambda\lambda 4959, 5007\) and \([\text{O}\,\text{ii}]\lambda 3727\). Region ‘B’ shows the opposite pattern: the most conspicuous line is \([\text{O}\,\text{iii}]\lambda 5007\), which is even brighter than \(\text{H}\alpha\). The spectrum of Region ‘C’ exhibits, along with a very weak \(\text{H}\alpha\) emission, high-contrast \(\text{Mg}\,\text{i}, \text{Fe}\) and \(\text{Ca}\) and Balmer-line absorptions. Such a spectrum is typical for a composite post-starburst region. We estimate the luminous-weighted age of the stellar population as 1.1–1.6 Gyr using the ulyss\(^1\) program package.

\(^1\) ulyss is an open code located at http://ulyss.univ-lyon1.fr/ and based on the papers of Koleva et al. (2009), Chilingarian et al. (2007) and other.
Figure 7. The diagnostic diagrams for various regions in Mrk 334. The top left-hand panel shows the mask used to select the galaxy regions, the [O III]-line isophotes are overlapped. The circles, asterisks, squares and triangles correspond to the nucleus and Regions ‘A’, ‘B’ and ‘C’, respectively. In the case of Region ‘C’, only spaxel contained emission-line spectra are shown. The black star shows the data by Lumsden et al. (2001). The solid black lines separate the domains corresponding to different excitation mechanisms. The grey lines show the grid of shock + precursor models from Allen et al. (2008) for \( n = 1 \text{ cm}^{-3} \) and solar elemental abundances. The thin and bold grey lines mark the contours of constant magnetic parameter, \( B/n^{1/2} = 0.1, 0.5, 1.0, 2.0, 5.0, 10 \mu \text{G cm}^{3/2} \), and contours of constant velocity, \( v = 250, 350, 450 \text{ km s}^{-1} \) (velocities increase from bottom to top), respectively.

Regions with different emission-line spectra must also differ in their ionization sources. We construct the diagnostic diagrams to determine the ionization mechanism for the inner regions of the galaxy. Given the line ratios for different excitation mechanisms, we can identify regions dominated by thermal (young stars), non-thermal (active nucleus) or shock ionization (hereinafter referred to as H II, AGN and LINER). Fig. 7 shows the most typical diagrams. In the diagrams, we adopted the boundaries separating domains corresponding to the different excitation mechanisms from Veilleux & Osterbrock (1987). We ignored the effect of internal extinction, because we use the intensity ratios of the lines with close wavelengths.

Mrk 334 is classified as a Sy 1.8-type galaxy and its Balmer-line profiles have a low-contrast broad component. We decomposed the H\( \alpha \) and H\( \beta \) line profiles into two Gaussian functions: one for the broad and one for the narrow component. Only the narrow component flux was used in the diagnostic diagrams.

The points in the diagrams of Fig. 7 show the line ratios in each MPFS spaxel. In all diagrams, the points corresponding to the nucleus lie at the H\( \alpha \)–LINER boundary. Here, the main ionization mechanisms are radiation of young stars and shocks, and not the non-thermal UV continuum as it is typical of an active nucleus. The points corresponding to the nucleus are located in the diagrams so far from the LINER–AGN boundary that the nucleus of Mrk 334 should be classified as a LINER rather than a Sy galaxy. This conclusion is consistent with the recent spectrophotometric studies of the nucleus reported by Lumsden et al. (2001). The asterisks in Fig. 7 indicate the line ratios in the nucleus as inferred from their long-slit spectrum. Fig. 7 demonstrates the good agreement between their data and our measurements for the nucleus except for the [S II]/H\( \alpha \) ratio. The last discrepancy must be due to the fact that we corrected our spectra for the atmospheric absorption band which partially overlaps with the [S II] lines and decreases sulfur flux by \( \sim 0.1 \) dex. Lumsden et al. (2001) say nothing about applying such a correction.

The emission-line ratios observed in the nucleus can be explained in terms of the following supposition. The star formation in the nucleus is so violent that the total line emission is determined mostly by the collective effect of photoionizing radiation of young stars and by the shocks produced by supernova explosions. At the same time, the emission lines of the active nucleus are barely visible against the circumnuclear starburst. The weak broad component with FWHM \( \approx 2500 \text{ km s}^{-1} \) in the hydrogen line profiles and Fe II features in the spectrum of the nucleus are the only indications of an AGN central engine.

In all diagrams, the points belonging to Knot ‘A’ lie deeply in the region corresponding to the ionization by OB stars radiation. Thus, ‘A’ is indeed a region of intense ongoing star formation. It

\(^2\) The fluxes reported by Lumsden et al. (2001) are extinction corrected, but, as we point out above, this correction is negligible for the diagrams.
The electron density is $n_T = \sigma / e \alpha$ instead of $e \alpha n$.

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The required shock speed is $250–350 \, \text{km s}^{-1}$.

The shock ionization contributes appreciably in the points located close to the nucleus.

Region ‘C’ may be satellite debris that has recently punched a hole in the gaseous disc of Mrk 334. It is located close to Region ‘B’; it appears sufficiently bright in the continuum images and its spectrum shows mostly stellar absorptions. In the diagnostic diagrams, Region ‘C’ lies in the H ii and LINER sectors. The photoionization is caused here mostly by star-forming processes, and the shock ionization contributes appreciably in the points located close to the nucleus.

5 KINEMATICS OF IONIZED GAS AND STARS

The Hα velocity field derived from the FPI data seems to be in a good agreement with the model of a regular rotating thin disc (Fig. 9). We fitted the velocity field by the ‘tilted-ring’ model using $100 \, \text{km s}^{-1}$ in other disc points, with the exception of the nucleus. More kinematic evidences will be presented in the next section.

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the algorithms employed earlier to study NGC 6104 (Smirnova et al. 2006). The circular rotation explains the gas velocity field fairly well. Therefore, we think that the inner tidal features \((r = 5–10\ \text{arcsec})\) are located outside the galaxy plane and do not perturb the entire gaseous disc but only cross it in some places. We found the disc inclination to be \(i_0 = 34^\circ \pm 6^\circ\) and the line-of-nodes position angle of \(PA_0 = 297^\circ \pm 3^\circ\). Fig. 10 shows the rotation curve of ionized gas \(\left(V_{\text{rot}}\right)\) and the radial variations of the kinematic axis \(\left(PA_{\text{kin}}\right)\). The data points in the range of \(r = 12–22\ \text{arcsec}\) come from three outer \(\text{H}\alpha\) regions located far from the central disc: \(PA_{\text{kin}}\) could not be determined from these regions, and we assume it to be equal to the mean \(PA_0\) of the disc.

The same figure shows kinematic parameters for the old stellar population. The rotation velocity measured for stars is about twice (by \(\sim 100\ \text{km s}^{-1}\)) smaller than that found for the ionized gas. This discrepancy must be due to asymmetric drift, because the central velocity dispersion of stars reaches, according to our estimates, 170–200 km s\(^{-1}\). The rotation curve of both gas and stars exhibits a characteristic peak near the effective radius of the bulge. At greater galactocentric distances, \(r = 4–12\ \text{arcsec}\), the rotation velocity of gas is almost constant and equal to 210–220 km s\(^{-1}\). The \(V_{\text{rot}}\) of the external \(\text{H}\alpha\) regions mentioned above is lower by 40–50 km s\(^{-1}\), however, we have no grounds to believe that these regions may be located outside the disc of the galaxy. It seems to be more likely that the formal decrease of the rotation velocity results from a contribution of non-circular gas motions.

Small variations of \(PA_{\text{kin}}\) at \(r < 5\ \text{arcsec}\) indicate the influence of the circumnuclear spiral on the kinematics of the gaseous and stellar subsystems. The \(PA_{\text{kin}}\) abruptly deviates from the line of nodes at \(r = 8–11\ \text{arcsec}\). Such a behaviour is indicative of large-scale non-circular motions at the edge of the \(\text{H} \alpha\) disc. The residual-velocity map (Fig. 9b) shows the distribution of observed velocities after the subtraction of the model. Deviations from circular rotation are small (15–20 km s\(^{-1}\)) in the regions with the brightest \(\text{H} \alpha\) emission. However, to the south from the nucleus an extended region can be seen where peculiar velocities are much higher and vary smoothly from \(-70\) to \(+60\ \text{km s}^{-1}\) in the east–west direction. Region ‘B’ is located here, which we have identified earlier by its spectro-photometric properties, primarily by its high \([\text{O} \text{iii}] / H_\alpha\) ratio. Now we see that this region is also distinguished by the peculiar kinematics of ionized gas. Such a velocity distribution corroborates the hypothesis – suggested above – that Region ‘B’ is the locus where the debris of the disrupted companion crossed the gaseous disc of the galaxy.

An alternative explanation of the observed gas kinematics is a jet–clouds interaction similar to that observed in Mrk 3 (Capetti et al. 1999) or Mrk 533 (Smirnova et al. 2007). However, this mechanism is unlikely for Mrk 334. First, we already pointed out above, this galaxy has no extended radio structure. Secondly, if the jet acts on the interstellar medium then the expected gradient of peculiar velocities should be directed away from the nucleus, i.e. in the radial and not in the azimuthal direction as we see in Fig. 9(b).

The velocity fields derived from the MPFS data (Fig.1) have allowed us to study the kinematics of gas in lines excited by different mechanisms, albeit with lower accuracy and in coarser detail compared to the results based on the FPI \(\text{H} \alpha\) data. The gas motions observed via most of the low-excitation emission lines \(([\text{O} \text{i}], [\text{N} \text{ii}], [\text{S} \text{ii}]\)) agree well with the picture found in the \(\text{H} \alpha\) line. Namely, they show a circular rotation with appreciable deviations near Region ‘B’. Only the velocity distribution in the \([\text{O} \text{iii}]\) line differs from the overall pattern (Fig. 1, bottom). Fig. 11 shows the residual velocities in this line after the subtraction of the circular-rotation model derived from the \(\text{H} \alpha\) data. Two features are apparent. First, the residual velocities in Region ‘B’ reach \(-150\ \text{km s}^{-1}\), which is greater by amplitude than the corresponding velocities for the low-excitation lines. Secondly, the galaxy nucleus shows a significant excess of negative velocities (down to \(-300\ \text{km s}^{-1}\)). Similar gas outflows from AGN (excess of ‘blue’ velocities, first and foremost, in the \([\text{O} \text{iii}]\) line) were found in the integral-field spectroscopy data for Seyfert galaxies studied by us and by other...
teams: Mrk 315 (Ciroi et al. 2005), NGC 2273 (Moiseev et al. 2004), NGC 2992 (Garcia-Lorenzo, Arribas & Mediavilla 2001), NGC 6104 (Smirnova et al. 2006) and others. A nuclear-blueshifted outflow associated with this feature is usually interpreted as a jet–clouds interaction (Ferruit 2002), or, in a more general case, as hot wind emerging from an active nucleus (Komossa et al. 2008), and references therein). However, the situation in Mrk 334 must be different. First, no radio jet can be seen in high-resolution radio maps, in any case, its size cannot exceed 0.5 arcsec. Secondly, in the nucleus itself the contribution from the non-thermal component to the ionization of gas is smaller than that of star formation (see Section 4). Thirdly, unlike the examples of active galaxies mentioned above, the high-velocity outflow in Mrk 334 is observed only in the [O\textsc{iii}] line. This outflow is most likely associated with intense star formation in the nucleus rather than with the central engine itself. Thus, what we observe in the [O\textsc{iii}] line is a low-density gas ejected above the plane of the galaxy as a result of multiple supernova explosions—the so-called ‘superwind’. Below we analyse this possibility in more detail.

We computed the velocity field of the stellar component by correlating the spectra of the galaxy with the stellar spectra from the MILES library and selecting the spectral type of the template and wavelength interval so as to maximize the amplitude of the cross-correlation function. Fig. 11 shows the velocity field corresponding to the old stellar population determined by cross-correlation of the galactic spectra with the spectrum of a K0 type star in the interval of λ5120–5800 Å. This velocity field was used to construct the stellar rotation curve presented in Fig. 10. However, a significant contribution of younger stellar population can be seen in the bluer part of the galaxy spectra in some regions. Thus, in the wavelength interval λ3750–4350 Å, the coefficient of correlation with the spectrum of a F-type star exceeds the corresponding value for a K-type star in the λ5100–5500 Å wavelength interval. The measurements made for the ‘old’ and ‘young’ populations yield different line-of-sight velocities. Fig. 11 shows the difference between the velocity fields of old and young stars. In the nucleus, the difference is small and does not exceed 20 km s\(^{-1}\), which is comparable to measurement errors. However, the velocity difference reaches ~80 km s\(^{-1}\) in two regions to the east of the nucleus. Both regions identified in the field of stellar residual velocities coincide with the inner tidal loops in the circumnuclear region, including Region ‘C’ (Fig. 5b). These facts lead us to suggest that here we see two kinematic components along the same line of sight. The old stellar population belongs to the disc of Mrk 334 and exhibits normal circular rotation. At the same time, the tidal filaments formed in the process of the companion disruption are dominated by younger population (as a result of a relatively recent burst of star formation). The filaments are located outside the disc plane as is evident from their line-of-sight velocities. Fig. 11(c) also shows another region with significant negative differences of the young and old stars velocities to the west from the nucleus. It may also include stars from the companion galaxy.

An interesting pattern emerges if we cross-correlate the spectra in the NaD doublet spectral domain. Fig. 11 shows the line-of-sight velocities for this line measured after the subtraction of the velocity field of the old stellar component. An excess of negative residual velocities up to ~180 km s\(^{-1}\) is immediately apparent in the nucleus of the galaxy. The NaD line is present not only in the spectra of late-type stars but also in the spectra of the interstellar medium. It is reasonable to associate the excess velocities in this line with the same superwind that we found in the [O\textsc{iii}]-line data for the ionized gas. We should note that outflow velocities may be underestimated because the contamination of the NaI line by absorption from the stellar population is also present.

6 X-RAY RADIATION OF MRK 334

Let us now briefly discuss the peculiarities of the distribution of X-ray flux of Mrk 334 according to the ROSAT data. Zimmermann et al. (2001) report isophotes of the smoothed image in the energy interval of 0.1–2.4 keV. The X-ray source with the luminosity of \(L_X = 2.6 \times 10^{42} \text{erg s}^{-1}\) is unambiguously identified with the galaxy. However, the contours of the X-ray image are appreciably offset with respect to the optical nucleus, and outer isophotes coincide with the tidal structures at \(r = 70–100\) arcsec north-west and south-west of the centre of the galaxy (Fig. 12). Hence, the diffuse X-ray emission is associated with the merging galaxy system but not with the Seyfert nucleus. Especially striking is the almost exact coincidence of the outer X-ray isophotes with the edges of optical filaments which is surprising given the relatively low spatial resolution of the ROSAT data.

If the most of the X-ray radiation of Mrk 334 is unassociated with the active nucleus, it may be due either to unresolved stellar sources or to the outer hot gas. We believe the former variant to be unlikely. Excess number of X-ray point sources – close binaries, ultraluminous X-ray sources, young supernova remnants associated with a starburst – are observed in a number of interacting galaxies. In this case, other signs of ongoing star formation and, in particular, H\textsc{ii} regions, should also be apparent at the periphery of the galaxy. However, according to our data, H\textsc{ii} emission is concentrated only in the central region, inside \(r < 12\) arcsec.

If the source of the emission is hot gas then where does it come from? It cannot be the corona of the disrupted companion like those observed in giant elliptical galaxies, because the mass of the companion is not too large, and Mrk 334 is a disc galaxy. An H\textsc{i} corona may have formed from the gas scattered as a result of interaction, whereas most of this gas is concentrated in the disc plane. It is, however, unclear how this gas can be heated.

We could suggest only one more or less realistic scenario to explain the formation of the extended X-ray structure. The inner parts of the galaxy are marked by high SFR. Our estimates yield SFR = 18 M\(_\odot\) yr\(^{-1}\) (from the H\textalpha{} line) and 12 M\(_\odot\) yr\(^{-1}\) [as inferred from

Figure 12. The R-band image of the galaxy with ROSAT X-ray isophotes from Zimmermann et al. (2001) superimposed.
the IRAS FIR using the relations from Kennicutt (1998b)]. Such an intense star-forming activity in a compact region accompanied by supernova explosions may give rise to a superwind phenomenon that manifests in significant heating of the interstellar medium and its outflow within a wide cone perpendicular to the galaxy disc (Heckman, Armus & Miley 1990; Veilleux, Cecil & Bland-Hawthorn 2005). Inside the cone, the temperature may rise to $10^7$ K, and hence the gas should be a powerful X-ray source. The starburst starts early enough during the interaction of galaxies — it begins before the complete disruption and merger of the companion. As an example, we can mention the well-known superwind galaxy M 82 that is currently in the process of a tidal interaction with M 81, or the NGC 6285/6286 galaxy pair (Shalyapina et al. 2004). Thus, a hot gaseous ‘bubble’ or cone could be formed above the plane of Mrk 334 even before the final stage of the merging. The spatial distribution of the hot gas was then distorted because of the significant perturbations of the gravitational potential of the system. We observe the result of these distortions as the offset of the X-ray brightness centre in the sky-plane projection.

We have already pointed out in Section 5 that the MPFS spectra are indicative of the presence of the superwind in Mrk 334. Gas motions directed towards the observer have been found in the central region. The observed velocities (180–300 km s$^{-1}$) are typical of superwind galaxies with intense star formation in their nuclei (Veilleux et al. 2005).

7 DISCUSSION

The analysis of various observational data lead us to conclude that Mrk 334 is in the process of merging with a companion that has already been almost completely disrupted by the tidal forces. Is the nuclear activity associated with such a close interaction? Let us first turn to the galaxy morphology. The inner region ($r \leq 3$ kpc) hosts a well-defined spiral pattern (Fig. 5c). Nuclear spirals in Mrk 334, where sites of star formation are located, are relatively brighter than similar features in other galaxies (Deo, Crenshaw & Kraemer 2006). The luminous H II Region ‘A’ located in the western spiral arm has the size typical of giant star-forming complexes in nearby spiral galaxies. Infrared and UV observations (Rothberg & Joseph 2004; Muñoz Marin et al. 2007) confirm that Mrk 334 is a starburst galaxy. This explains why in the ionization diagrams the part of the data points that belong to the nucleus lie in the domain corresponding to the ionization by young stars.

Such a powerful burst of star formation in a rather compact region produces a hot gas superwind. Low-density gas heated by frequent supernova explosions forces its way through the dense and cold gas of the disc to form a wide-cone outflow in the direction perpendicular to the galaxy plane. Superwind is usually most conspicuous in edge-on galaxies with the cone of hot gas fully open towards the observer. However, Mrk 334 has a less convenient orientation and the cone is seen projected against the bright disc of the galaxy and hence the conclusions about the presence of a superwind are to be based on the circumstantial evidences. First, negative [O III]-line velocities are observed towards the nucleus of the galaxy (the base of the outflow) suggesting outward motions of highly ionized gas with velocities of 200–300 km s$^{-1}$ perpendicular to the galactic plane. Also, the 150–180 km s$^{-1}$ motions are observed in the NaD absorption line. The velocities are larger in the high-excited gas than in the neutral medium, which is typical for galactic winds (Veilleux et al. 2005).

A second indication of the superwind is provided by the observed asymmetry of the X-ray flux distribution with respect to the nucleus.

Interaction-related processes become important as close to the nucleus as at the distances of 1–2 kpc from it. We see their footprints as Regions ‘B’ and ‘C’ and a system of tidal arcs and envelopes extending out to galactocentric distances of 40 kpc. Fig. 13 shows schematically the inner region of the galaxy. An analysis of the kinematics of gas and stars led us to conclude that the orbits of the debris of the disrupted companion lie outside the disc of Mrk 334 and cross it at a considerable inclination. In the region of this cross-point, we observe a cavern with gas density lower than that of the ambient surrounding medium (Region ‘B’) which has formed as a result of the crossing of the disc by a dense stellar condensation. The rotation velocity at this location is 200–250 km s$^{-1}$, implying that the fragments of the companion also move with the velocities of the same order relative to the gaseous disc. Also, we find evidence of a high-velocity collision in the gas kinematics and ionization. The collision has strongly perturbed the velocity field in the $\sim 3$ kpc size region. The maximum amplitude of the line-of-sight velocity perturbations amounts to 70 km s$^{-1}$ in low-excitation lines and reaches 150 km s$^{-1}$ in the [OII], because in this line we see low-density gas ionized by a powerful shock. The ionization state in Region ‘B’ can be described in terms of the shock + precursor model for a shock propagating at a speed of 250–350 km s$^{-1}$. The mutual agreement of all the three estimates for the collision velocity supports the adopted interpretation of the formation of Region ‘B’.

Unfortunately, in the literature we have not found any detailed simulations of the gaseous disc response to the intrusion of a self-gravitating body whose mass is small compared to that of the entire galaxy. As a close analogy, we can mention the paper by Levy (2000), that briefly analysed the response of a gaseous disc of a galaxy to the crossing by a globular cluster. Even in such a relatively small-scale collision, the resulting shock propagates to at least five to six vertical disc scale heights.

We believe that the remnant of the companion galaxy now observed as Region ‘C’ is the most likely candidate object to have punched the disc of Mrk 334 and produced there a cavern of hot gas. The line-of-sight velocities of the stellar population associated with Region ‘C’ differ appreciably (by almost 100 km s$^{-1}$) from the velocities of the old stellar population in the galactic disc. How is Region ‘C’ located with respect to the observer? Residual velocities of ionized gas in the cavern (Region ‘B’) are mostly negative. This means that the body that produced the cavern crossed the disc plane moving towards us and must now be located above the galaxy disc.
with respect to the observer (Fig. 13). Residual velocities of the young stellar population in Region ‘C’ are also negative implying that the nucleus of the companion traversed less than a quarter of its orbit after the collision. In accordance with the rotation curve, we estimate the dynamical age of the cavern in Region ‘B’ as $t \leq 10^7$ yr. Therefore, we indeed deal with a recent collision and the cavern has not yet cooled down or condensed.

Our photometric analysis of the tidal filaments yields a mass ratio for the interacting galaxies ranging from 1/5 to 1/3. The merger must have occurred between two gas-rich galaxies. Indeed, the total luminosity of non-axisymmetric features in the optical images is 25–30 per cent of the total luminosity of the galaxy. Hopkins et al. (2008) suggest that the ‘excess flux’ is even greater in the $K$ band where its contribution amounts to 45 per cent. According to Hopkins et al. (2008), such a high percentage of the excess flux can be reproduced in the model of gas-rich galaxies merging, and the process results in the formation of a LIRG galaxy, just as in the case of Mrk 334.

In Mrk 334, we appear to observe a transition from the LIRG stage to the phase of nuclear activity. The fact that the activity of the nucleus of the galaxy has started only recently is proved by weak water–ice absorptions in the infrared spectra that are indicative of a certain well-defined phase in the evolution of the object (Spoon et al. 2002).

Thus, both the burst of star formation and nuclear activity in Mrk 334 date back to a rather recent epoch and their age is comparable to the dynamic time-scale of the interaction. Li et al. (2002) pointed out, by references to Yuan et al. (in preparation), that ULIRGs experienced the stage of ‘diffuse merger’ when the nuclei of the interacting galaxies already merge together but have not yet formed a single nucleus. Composite activity – active nucleus + star formation – intensifies abruptly during this stage, and this appears to be now the case in Mrk 334.

8 CONCLUSIONS
We used 3D spectroscopic data and deep images to explore the structure and kinematics of the galaxy Mrk 334. The galaxy has a composite (AGN + starburst) nucleus and extended tidal structures in the form of loops and arcs observed at galactocentric distances ranging from 2 to 40 kpc. Extensive spectroscopic and photometric data allowed us to thoroughly analyse the structure of the inner regions of the galaxy. We consider the following points to be the most important.

(i) The main galaxy-to-companion mass ratio is about 3 to 5. The average surface-brightness profile shows a multilayered structure and can be decomposed into a bulge and two exponential discs. We caught the galaxy in the process of the formation of an outer LSB disc from the debris of the disrupted companion.

(ii) The central region of the galaxy demonstrates a powerful starburst that must have been triggered by the galaxy merger. Circumnuclear star formation is so intense that its contribution to the total ionization of gas exceeds that of the active nucleus. As a result, the corresponding data points in the diagnostic diagrams lie in the H ii/LINER domain. Such a powerful burst of star formation in a compact region gives rise to a superwind with velocities of 200–300 km s$^{-1}$. The asymmetric X-ray brightness distribution on ROSAT maps is consistent with this hypothesis.

(iii) We revealed a region $\sim 2$ kpc east of the centre that is possibly the nucleus of a disrupted companion. The spectrum of this region exhibits stellar absorptions that are typical of a region that has undergone a burst of star formation about one Gyr ago. The radial velocities of the stars located in this region differ appreciably from the stellar disc of Mrk 334 on to which it is projected. In the disc of the galaxy, we found a cavern filled with low-density ionized gas. We interpret this region as a site of a recent (about 10 Myr ago) crossing of the gaseous disc by the remnants of the disrupted companion. This supposition allows us to explain the unusually high $[O\,\text{iii}]/H\beta$ line ratio observed in this region that can be produced by a powerful shock propagating with a velocity of more than 250 km s$^{-1}$. The non-circular gas motions in this region agree with the crossing of the galaxy disc by the debris of the companion.

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REFERENCES
Afanasiev V. L., Moiseev A. V., 2005, Astron. Lett., 31, 193
Afanasiev V. L., Dodonov S. N., Moiseev A. V., 2001, in Ossipkov L. P., Nikiforov I. I., eds, Stellar Dynamics: from Classic to Modern. Sobolev Astronomical Institute, Saint Petersburg, p. 103
Allen M. G., Groves B. A., Dopita M. A., Sutherland R. S., Kewley L. J., 2008, ApJS, 178, 20
Barnes J. E., Hernquist L. E., 1991, ApJ, 370, L65
Barth A. J., Bentz M. C., Greene J. E., Ho L. C., 2008, ApJ, 683, L119
Bekki K., Shioya Y., Whitting M., 2006, MNRAS, 371, 805
Capetti A., Axon D. J., Macchetto F. D., Marconi A., Winge C., 1999, ApJ, 516, 187
Chilingarian I., Prugniel Ph., Sil’chenko O., Koleva M., 2007, in Vazdekis A., Peletier R. F., eds, Proc. IAU Symp., Vol. 241, Stellar Populations as Building Blocks of Galaxies, Cambridge Univ. Press, Cambridge, p. 175
Ciocci S., Afanasiev V. L., Moiseev A. V., Botte V., Di Mille F., Dodonov S. N., Rafanelli P., Smirnova A. A., 2005, MNRAS, 360, 253
Dahari O., 1985, AJ, 90, 1772
De Robertis M. M., Yee H. K. C., Hayhoe K., 1998, ApJ, 496, 93
Deo R. P., Crenshaw D. M., Kraemer S. B., 2006, AJ, 132, 321
Erwin P., Beckman J. E., Pohlen M., 2005, ApJ, 626, L81
Ferruit P., 2002, Rev. Mex. Astron. Astrofis. Ser. Conf., 13, 183
García-Lorenzo B., Arribas S., Mediavilla E., 2001, A&A, 787, 2001
Gonzalez Delgado R. M., Perez E., Tadhunter C., Vilchez J. M., Rodríguez-Espinosa J. M., 1997, ApJS, 108, 155
Heckman T. M., Armus L., Miley G. K., 1990, ApJS, 74, 833
Hopkins P. F., Hernquist L., Cox T. J., Dutta S. N., Rothenberg B., 2008, ApJ, 679, 156
Hunt L. K., Malkan M. A., Salvatii M., Mandolesi N., Palazeti E., Wade R., 1997, ApJS, 108, 229
Kennicutt R. C. Jr., 1998a, ARA&A, 36, 189
Kennicutt R. C. Jr., 1998b, ApJ, 498, 541

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Knapen J. H., 2005, Ap&SS, 295, 85
Koleva M., Prugniel Ph., Bouchard A., Wu Y., 2009, A&A, 501, 1269
Komossa S., Xu D., Zhou H., Storchi-Bergmann T., Binette L., 2008, ApJ, 680, 926
Levy V. V., 2000, A&A Trans., 18, 621
Li C., Kauffmann G., Heckman T. M., White S. D. M., Jing Y. P., 2008, MNRAS, 385, 1915
Lumsden S. L., Heisler C. A., Bailey J. A., Hough J. H., Young S., 2001, MNRAS, 327, 459
Maiolino R., Ruiz M., Rieke G. H., Papadopoulos P., 1997, ApJ, 485, 552
Martini P., 2004, in Storchi-Bergmann T., Ho L. C., Schmitt H. R., eds, IAU Symp., Vol. 222, The Interplay Among Black Holes, Stars and ISM in Galactic Nuclei. Cambridge Univ. Press, Cambridge, p. 235
Martini P., Pogge R. W., 1999, AJ, 118, 2646
Martini P., Pogge R. W., Ravindranath S., An J. H., 2001, ApJ, 562, 139
Moiseev A. V., 2001, Bull. Spec. Astrophys. Obs., 51, 11
Moiseev A. V., 2002, Bull. Spec. Astrophys. Obs., 54, 74
Moiseev A. V., Egorov O. V., 2008, Astrophys Bull., 63, 193
Moiseev A. V., Valdés J. R., Chavushyan V. H., 2004, A&A, 421, 433
Muñoz Martín V. M., González Delgado R. M., Schmitt H. R., Cid Fernandes R., Pérez E., Storchi-Bergmann T., Heckman T., Leitherer C., 2007, AJ, 134, 648
Osterbrock D. E., 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei. University Science Books, Mill Valley, CA
Pérez García A. M., Rodríguez Espinosa J. M., 2001, ApJ, 557, 39
Rothberg B., Joseph R. D., 2004, AJ, 128, 2098

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