Very metal-poor galaxies: ionized gas kinematics in nine objects

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ABSTRACT
The study of ionized gas morphology and kinematics in nine extremely metal-deficient (XMD) galaxies with the scanning Fabry–Perot interferometer on the Special Astrophysical Observatory (SAO) 6-m telescope is presented. Some of these very rare objects (with currently known range of O/H of 7.12 < 12 + log(O/H) < 7.65, or Z⊙/35 < Z < Z⊙/10) are believed to be the best proxies of ‘young’ low-mass galaxies in the high-redshift Universe. One of the main goals of this study is to look for possible evidence of star formation (SF) activity induced by external perturbations. Recent results from H i mapping of a small subsample of XMD star-forming galaxies provided confident evidence for the important role of interaction-induced SF. Our observations provide complementary or new information that the great majority of the studied XMD dwarfs have strongly disturbed gas morphology and kinematics or the presence of detached components. We approximate the observed velocity fields by simple models of a rotating tilted thin disc, which allows us the robust detection of non-circular gas motions. These data, in turn, indicate the important role of current/recent interactions and mergers in the observed enhanced SF. As a by-product of our observations, we obtained data for two Low Surface Brightness (LSB) dwarf galaxies: Anon J012544+075957 that is a companion of the merger system UGC 993, and SAO 0822+3545 which shows off-centre, asymmetric, low star formation rate star-forming regions, likely induced by the interaction with the companion XMD dwarf HS 0822+3542.

Key words: galaxies: dwarf – galaxies: evolution – galaxies: individual: (UGC 772, HS 0122+0743, SBS 0335–052E and W, HS 0822+3542, SDSS J1044+0353, SBS 1116+517, SBS 1159+545, HS 2236+1344, SAO 0822+3545) – galaxies: interactions – galaxies: kinematics and dynamics – galaxies: starburst.

1 INTRODUCTION
The group of very rare dwarf galaxies with gas metallicities Z below Z⊙/10 (or 12 + log(O/H) < 7.65, e.g. review by Kunth & Östlin 2000) are called extremely metal-deficient (XMD) galaxies. Such objects comprise only about two per cent of known blue compact galaxies (BCGs), low-mass galaxies with active star formation (SF) (e.g. Pustilnik et al. 2005a). The latter, in turn, comprise about 6 per cent of the entire local dwarf galaxy population (Lee et al. 2009, and references therein). Thanks to intensive searches for new XMD galaxies in several recent large surveys (e.g. Melbourne & Salzer 2002; Kniazev et al. 2003; Pustilnik et al. 2003c; Ugryumov et al. 2003; Pustilnik et al. 2005a; Brown, Kewley & Geller 2008; Papaderos et al. 2008; Guseva et al. 2009, among others, and references therein), the number of currently known such objects in the local Universe is about 100. There is also progress in identification of such objects at large redshifts (Kakazu, Cowie & Hu 2007).

The interest in these atypical, local Universe galaxies is caused by the similarity of their properties to low-mass galaxies in the early Universe, when the typical metallicity of galaxies was one to two orders of magnitude smaller than the solar one. Therefore, understanding the specific processes of SF and evolution in nearby galaxies with such low metallicity will provide insights into similar processes in young galaxies at high redshifts. To better understand various aspects of XMD galaxies SF and evolution, we conduct an extensive study of a subsample of XMD galaxies in optical, near-infrared (NIR) and radio domains (e.g. Pustilnik et al. 2003a, 2004a; Pustilnik, Kniazev & Pramskij 2004b, 2005b; Pustilnik & Martin 2007; Ektä, Chengalur & Pustilnik 2008; Pustilnik, Tepliakova & Kniazev 2008; Ektä, Pustilnik & Chengalur 2009).

One of the fundamental questions of SF in low-mass, gas-rich galaxies is the trigger mechanisms of starbursts: whether the
intrinsic instabilities in gas discs are capable to produce the observed level of enhanced (bursting) SF (e.g. models by Pelupessy, van der Werf & Icke 2004; Di Matteo et al. 2008; observations of Virgo cluster dIrrs by Brosch, Almoznino & Heller 2004, and references therein), or external mechanisms (such as tidal disturbances and mergers) are necessary in a significant fraction of observed starbursts.

From the analysis of the density distribution in BCGs in comparison to more typical late-type dwarfs, Salzer & Norton (1999) concluded that the former have a higher gas concentration and, therefore, BCGs represent a special group of galaxies, more susceptible to internal instabilities and related starbursts. But it is unknown whether this is an inherent property of BCG progenitors or this higher gas concentration appeared due to a minor merger or as a result of a recent interaction with a barely detectable companion. If due to mergers or interactions, BCG progenitors could be the quite common late-type dwarfs. To disentangle the possible scenarios, one needs a large, representative sample of starbursting galaxies with well studied and understood kinematics of both H\textsc{i} and ionized gas. This is required to determine the prevalence of external or internal disturbances.

First statistical indications for the possible importance of interactions to trigger starbursts in BCG progenitors was presented by Taylor et al. (1995) in their search for H\textsc{i}-rich companions in a small BCG sample. For a larger BCG sample, the conclusion on the high fraction of interaction-induced starbursts was made by Pustilnik et al. (2001a, see also Noeske et al. 2001), based on the comparison of observed relative distances and ‘threshold tidal distances’, at which a perturber galaxy should induce shocks in the gas disc and produce dissipation of gas angular momentum (as suggested by Icke 1985). While that study was indicative of the important role of collisions in starbursts of gas-rich low-mass galaxies, more elaborate tests should be used to clear up the real role of external factors in starbursts. In turn, numerous studies of galaxy morphology and kinematics at redshifts of up to \( \sim 1 \) (e.g. Puech et al. 2006; Yang et al. 2008) show clear indications on the importance of external mechanisms on the enhanced SF in a significantly larger galaxy fraction than at the current epoch.

In many cases, the traces of interactions can be hidden if only images of stellar components are available. Therefore, gas morphology and kinematics provide a better tracer of interaction-induced starbursts. To this end, H\textsc{i} mapping is a good way for galaxies with sufficiently large H\textsc{i} flux. For less gas-rich and/or more distant galaxies, the study of the ionized gas kinematics can be a good complementary technique. Besides, this method provides usually a finer angular resolution and allows comparison of the global gas kinematics derived from H\textsc{i} mapping with the gas motions within the region of higher density, around the sites of SF. These kind of studies, initiated by Östlin et al. (1999, 2001) for a small sample of luminous BCGs, already provide good evidence for merger-induced SF in such objects. Some indications for the same phenomenon have been observed by García-Lorenzo et al. (2008) for a group of five other luminous BCGs and by Pérez-Gallego et al. (2010) for representatives of the similar group of luminous compact blue galaxies.

The starbursting XMD galaxies are especially interesting in this aspect, since the results may have implications for cosmological young galaxies in the high-redshift Universe. The evidence of significantly disturbed optical morphology and interactions, indicating an unrelaxed state of many XMD galaxies, was already noticed by us (e.g. Pustilnik et al. 2004b, 2005b, 2006) and more recently by Papaderos et al. (2008). How does this relate to the origin of XMD galaxies?

There are several options for evolutionary scenarios of XMD dwarf galaxies, already emphasized in the literature (e.g. Pustilnik et al. 2005b). Two of them relate to gas-rich discs, which are very stable locally, and being isolated, have been evolving very slowly (like LSB galaxies). Some of them might even remain dark objects (e.g. Pustilnik 2008) and thus ‘pristine’ like protogalaxies at epochs of the major galaxy formation. Such galaxies would be very difficult to discover/recognize before they (by chance) have experienced a strong external perturbation due to an interaction with a galaxy-sized mass. When this happens, such galaxies can lose their global stability and experience a substantial SF burst. Due to their slow evolution, during the starburst, they would appear as gas-rich and very metal-poor (XMD) objects. Therefore, the study of gas kinematics for the sample of XMD galaxies can shed light on their origin as a group, or can give clues to the diversity of their properties and their finer classification.

In this paper, we present the results of an H\textalpha study of the ionized gas kinematics in nine XMD starbursting galaxies (BCGs) conducted with the SAO 6-m telescope’s scanning Fabry–Perot interferometer (FPI). These galaxies constitute a part of a larger XMD galaxy sample, for which we conduct a multiwavelength study of their properties. Most were selected for this FPI H\textalpha study due to their unusual or disturbed optical morphology. For a fraction of them, the H\textsc{i} mapping data are available, which provide an opportunity of the combined view on the gas kinematics. We plan to continue this project for a larger sample of XMD starbursting galaxies in order to improve statistics and to search for possible differences in the properties of the ionized gas kinematics.

Due to volume limitations, the scope of this paper is kept mainly to observational results for the studied XMD galaxy subsample and their preliminary analysis. The more advanced analysis, involving multiwavelength data and new methods of modelling (like suggested by Barnes & Hibbard 2009), will be presented for individual galaxies in forthcoming papers. This paper is organized as follows: in Section 2, we describe observations and their reduction. Section 3 presents the description of data analysis and the summary of results. In Section 4, the kinematic properties are discussed in more detail and are compared with other data on these BCGs, and their likely interpretation is suggested. Section 5 summarizes conclusions of this study.

### 2 Observations and Data Reduction

The observations of XMD galaxies were conducted with the multi-mode instrument SCORPIO (Afanasiev & Moiseev 2005) installed in the prime focus of the SAO 6-m Big Telescope Azimuthal (BTA) during three runs (see Table 1 for details and Table 2 for galaxy properties).

#### Table 1. Log of the 6-m telescope FPI observations.

| Object | Date (dd.mm.yy) | Exposure time (s) | Ang. resol. (arcsec) |
|--------|----------------|-------------------|---------------------|
| SDSS J0113+0052 | 11.01.07 | 36 × 200 | 4.0 |
| HS 0122+0743 | 10.01.07 | 2 × 36 × 90 | 2.3 |
| SBS 0335−052W | 14.01.08 | 2 × 36 × 150 | 1.4 |
| SBS 0335−052E | 14.01.08 | 2 × 36 × 150 | 1.4 |
| HS 0822+3542 | 10.01.07 | 36 × 250 | 1.4 |
| SDSS J1044+0353 | 14.01.08 | 36 × 150 | 1.4 |
| SBS 1116+517 | 10.01.07 | 36 × 250 | 1.5 |
| SBS 1159+545 | 14.01.08 | 36 × 170 | 1.8 |
| HS 2236+1344 | 08.09.05 | 36 × 250 | 1.0 |
### Table 2. Parameters of nine XMD and two by-product (below the line) galaxies.

| IAU name | Coord. (2000.0) | $V_{hel}$ | $B_{hel}$ | $M_B^{hel}$ | O/H | F(Hα) | $D$ | Scale | Alternative name |
|----------|-----------------|-----------|-----------|-------------|-----|-------|-----|-------|-----------------|
|          | RA h m s        | Dec. ° ′ ′ | km s$^{-1}$ | mag         | mag |               | Mpc | pc arcsec$^{-1}$ | name            |
| 1        |                 |           |           |             |     |       |     |       |                 |
| SDSS J0113+0052 | 01 13 39.40 | +00 52 27.9 | 1176 ± 1 | 16.28$^1$ | −14.70 | 7.24 | 6.8 | 16.3 | 79 UGC 772 |
| HS 0122+0743  | 01 25 34.18 | +07 59 22.2 | 2940 ± 2 | 15.48$^2$ | −17.76 | 7.63 | 20.0$^2$ | 40.3 | 195 UGC 993 |
| SBS 0335–052W | 03 37 38.46 | −05 02 36.3 | 4038 ± 2 | 19.14$^4$ | −14.73 | 7.12 | 1.4$^4$ | 53.8 | 261           |
| SBS 0335–052E | 03 37 44.04 | −05 02 37.6 | 4053 ± 2 | 16.95$^4$ | −16.92 | 7.29 | 32.0$^4$ | 53.8 | 261           |
| HS 0822+3542  | 08 25 55.43 | +35 32 31.9 | 727 ± 2  | 17.92$^5$ | −12.49 | 7.45 | 7.6$^6$ | 13.5 | 65            |
| SDSS J1044+0353 | 10 44 57.84 | +03 53 13.2 | 3865 ± 1 | 17.62$^5$ | −16.20 | 7.44 | 14.5 | 53.8 | 261           |
| SBS 1116+517  | 11 19 34.29 | +51 30 10.7 | 1342 ± 2 | 17.14$^5$ | −14.70 | 7.51 | 15.2 | 23.1 | 112 Arp’s     |
| SBS 1159+545  | 12 02 02.36 | +54 15 50.1 | 3592 ± 1 | 19.00$^2$ | −14.60 | 7.49 | 5.5  | 52.2 | 255           |
| HS 2236+1344  | 22 38 31.15 | +14 00 28.6 | 6162 ± 2 | 17.88$^2$ | −16.90 | 7.50 | 12.0$^2$ | 86.4 | 419           |
| Anon J012544+075957 | 01 25 44.18 | +07 59 57.0 | 3012 ± 3 | 17.0$^2$ | −16.30 | 1.5  | 40.3 | 195           |
| SAO 0822+3545 | 08 26 05.59 | +35 35 25.7 | 742 ± 2  | 17.56$^3$ | −12.85 | 0.4  | 13.5 | 65            |

$^a$Systemic velocity on our Hα data. For UGC 993, this is a mean of $V_{hel}$ for E and W components; for SAO 0822+3545, this is Hα velocity from Chengalur et al. (2006).

$^b$Photometry data are from: 1 Smoker, Davies & Axon (1996); 2 Pustilnik et al. in preparation; 3 Pustilnik et al. (2003a); 4 Pustilnik et al. (2004b); 5 NED/Sloan Digital Sky Survey (SDSS) transformed from $g, r, B$; 6Moustakas & Kennicutt (2006) for Hα flux.

$^c$Corrected for $A_B$ (according to Schlegel, Finkbeiner & Davis 1998), with distances from Column 9.

$^d$In units 12 + log(O/H). Data are from Ugyumov et al. (2003), Kniazev et al. (2003), Izotov & Thuan (2007), Izotov, Thuan & Guseva (2005).

$^e$In units of $10^{-14}$ erg cm$^{-2}$s$^{-1}$; Hα fluxes adopted from literature are coded as photometry data.

$^f$From NED [Virgo-infill]; $H_0 = 73$, except HS 0822+3542/SAO 0822+3545, for which additional correction is adopted (see text).

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**3 RESULTS AND ANALYSIS**

In Table 2, we present the summary of the main observational parameters of the studied XMD galaxies. Since the accuracy of our total Hα flux estimates (10–30 per cent) is in general worse than that for dedicated Hα photometry, we give our values only for unknown Hα fluxes. For the remaining objects, we cite data from the literature. Absolute magnitudes, $M_B$, are calculated for distances taken from NASA/IPAC Extragalactic Database (NED), except for HS 0822+3542 and its companion LSB dwarf. As discussed in Pustilnik et al. (2010), they are situated in the region with large peculiar negative radial velocities ($\sim 300$ km s$^{-1}$) due to the effect of the huge Local Void (Tully et al. 2008). To derive their distances, this peculiar velocity was accounted for.

The dominant or important mode of gas motions in late-type, low-mass isolated galaxies (even for objects with luminosities corresponding to $M_B$ fainter than $−14.0$) is rotation in a gravitational field of a dark matter (DM) halo and baryonic disc (e.g. Begum et al. 2006, 2008, and references therein). Two types of processes can significantly affect the regular velocity field attributed to rotation: the SF activity and tidal interactions.

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1 http://nedwww.ipac.caltech.edu/
3.1 Kinematics of SF induced shells

The strong SF activity releases a significant amount of kinetic and thermal energy in short periods, and it results in the formation of hot bubbles and shells with typical sizes of 100 pc to about 1 kpc. Such shells, with maximal observed line-of-sight velocities in the range of 10 to 100 km s\(^{-1}\) are recognized in both long-slit spectra and 2D H\(_\alpha\) velocity fields of star-forming galaxies (e.g. Martin 1996, 1998; Zasov et al. 2000; Pustilnik et al. 2003b; Lozinskaya et al. 2006; Martinez-Delgado et al. 2007; Bordalo, Plana & Telles 2009, among others). In principle, the large-scale velocity fields in such expanding ionized shells are sufficiently simple. However, in case of dwarf galaxies, which have relatively small rotation velocities, shells can significantly perturb the disc velocity field. In Appendix A, we present the simulated velocity field of dwarf galaxies with shells for several simple cases. Using the characteristic parameters typical of our sample (disc size, inclination, rotation curve, etc.), we describe the technique for such shells’ recognition and masking in the observed velocity fields. Fortunately, in many simple theoretical scenarios, it is possible to extract the real parameters of global rotation, even when the shell expansion velocity is larger than the line-of-sight projection of global rotation on given radii.

3.2 External perturbations of velocity fields

It is not yet well understood how the strength of starbursts and that of related expanding bubbles are connected with internal or external triggers. But since the external perturbations (e.g. due to galaxy collisions or extragalactic cloud infall) provide disturbances which are additional to internal ones, they are naturally expected to trigger the stronger disturbances in galactic gas and to result in more intense SF. Besides, in general, the characteristic time-scales of singular star-forming events in isolated low-mass galaxies (of ten to several tens of Myr) are shorter than those for the events induced by external interactions. The latter are comparable to rotation periods, and usually are of the order of 100 Myr and more, the typical time-scale for galaxy response to a collision-induced perturbation (e.g. Di Matteo et al. 2008, and references therein).

This is due to different spatial scales involved in such SF episodes. For internal perturbations we usually have some local enhancement, while for external ones the gas flows on scales of the whole galactic disc are involved. Therefore, one can expect rather different effects in isolated and interacting starbursting galaxies. In the former, the gas velocity field should display the characteristic rotation pattern with rather localized disturbances due to the starburst-related shells. More or less typical dIrr galaxies can serve as templates for such kinematics. In the interaction-induced starbursts one can observe, besides the overall rotation and the appearance of shell kinematics, the effects of tidally disturbed velocity fields to various degrees. In extreme cases of a major merger, the strong disturbance of the initial equilibrium rotation field can almost wash out the regular component.

Apart from non-destructing (fly-by) collisions, various types of mergers (major, intermediate mass-ratio and minor \([M_1:M_2 > 5]\)) can trigger late-type galaxy starbursts. Depending on the stage and mass proportion, the velocity fields can show various patterns – from very disturbed with no traces of regular rotation to more or less regular rotation with residual motions (e.g. counter rotation in the central region, where a smaller component has sunk as the result of minor merger). As recent simulations demonstrate (e.g. Kronberger et al. 2006; Pedrosa et al. 2008), the bifurcations in velocity curves should appear (that is prominent asymmetries in...
receding and approaching branches of rotation curves) as a result of close recent encounters. Various appearances of complex velocity fields resulting from major mergers of disc galaxies were demonstrated by Jesseit et al. (2007).

### 3.3 Fitting results

From the above discourse, it is clear that it is quite natural to analyse Hα velocity fields in the studied XMD dwarf galaxies by trying to fit them with a model of a flat rotating disc and to compare the residual velocity field against various patterns characteristic of shells, warps, central counter-rotation, discontinuities, etc. Of course, the morphology of both stellar continuum and Hα emission should be taken into account in the course of the results’ interpretation.

We analysed the velocity fields using the well-known approximation of a thin rotating disc (‘tilted-rings’ method), which is generally accepted in the analysis of gas kinematics. For the method description and references to the original works, see Moiseev, Val’des & Chavushyan (2004). This method calculates the disc orientation parameters (major axis PA, inclination \(i\), systemic velocity \(V_{\text{sys}}\)) together with radial variations of the rotation velocity \(V_{\text{rot}}\). In special cases of non-circular motions, we can also estimate radial dependencies of PA and \(V_{\text{sys}}\).

In Table 3, the ‘best-fitting’ model parameters are summarized: systemic velocity \(V_{\text{sys}}\), position angle PA and inclination angle \(i\), along with relevant brief comments. Unfortunately, from the kinematic model, we could only derive \(i\) for three galaxies, whose inclinations are indicated with errors in the Table 3. For J0113+0052 and SAO 0822+3545, we adopted the inclinations from published H\(\alpha\) maps. In the remaining cases, to estimate the inclination angle, we adopted the approach based on the morphology of the overall H\(\alpha\) emission and the observed ratio of minor to major axis of H\(\alpha\) ‘ellipsoid’ \(p = a/b\). Assuming that this reflects the real gas distribution for an inclined ‘thick’ (typical of dwarf galaxies) disc with the intrinsic axial ratio \(q\), we estimated the inclination \(i\) with well-known formula \([\cos(i)]^2 = (p^2 - q^2)/(1 - q^2)\). The estimate of parameter \(q\) was adopted according to formula A6 from Staveley-Smith, Davies & Kinman (1992). We understand that in many cases, where we infer strong disturbances in morphology and velocity field, the above assumption can be hardly justified, and hence the adopted inclination angle and the related amplitude of rotation velocity can be rather uncertain. But the concrete choice of \(i\) does not affect the overall radial dependence of the model rotation velocity. A more detailed description of the data and their model fits, along with discussion of relevant kinematics and morphology in H\(\alpha\)-line and other points are presented for each individual galaxy in Section 4.

For each of the nine programme XMD galaxies and for two ‘by-product’ LSB dwarf galaxies, we show the related graphic materials in Figs 2–4. The colour images of velocity field data are available in electronic version of the journal. They are arranged in columns of six images in the following order. The first (top) panel displays continuum image in g-filter from the SDSS or in the blue band from the digitized Palomar Observatory Sky Survey (POSS). For SBS 0335–052E,W, the BTA B-band images are used from Pustilnik et al. (2004b). The brightness distribution is shown in logarithmic scale. The second panel shows the image of integrated emission in the H\(\alpha\) line in logarithmic scale. The third panel shows the velocity field, both in colour and by isovelocility lines. In the fourth panel, we show the ‘best-fitting’ model of thin tilted rotating disc. The fifth panel presents, in colour, the residual velocity field (observed minus model) and in the sixth panel the velocity dispersion is shown in colour. For both panels, the intensity of H\(\alpha\)-line is superimposed by contours. The radial dependence of \(V_{\text{rot}}\) for the ‘best-fitting’ models of the programme galaxies is presented in Fig. 5.

### 4 DISCUSSION

The issue of strong interactions of star-forming galaxies in the aspect of their evolution is actively studied in recent times (e.g. Puech et al. 2006; Di Matteo et al. 2008; Yang et al. 2008, and references therein). Also, many N-body simulations are performed to allow both qualitative and quantitative (with more detailed data) classification of observed velocity fields to originate due to strong interactions or mergers (e.g. Kronberger et al. 2006; Jesseit et al. 2007). There is also substantial progress in morphology analysis to assign galaxies to merger products (Conselice 2003; Lotz et al. 2008, and references therein).

The main goal of these FPI H\(\alpha\) study was to search for the possible appearances of unusual, highly disturbed, asymmetric velocity fields in the ionized gas kinematics. The latter might indicate sufficiently strong interactions or various stages of minor or major mergers. This would allow us to make the first step to quantify the role of interactions in active SF of XMD galaxies. Of course, in

### Table 3. Parameters of model rotating discs for observed galaxies.

| IAU name          | \(V_{\text{sys}}\) | PA (°) | \(i\) (°) | Brief comments                  |
|-------------------|-------------------|-------|----------|---------------------------------|
| J0113+0052        | 1173 ± 1          | 199 ± 5 | 40\(^a\) | UGC 772. S component is detached. Probable minor merger |
| 0122+0743W        | 2953 ± 2          | 295 ± 5 | 37 ± 4   | UGC 993W. component of major merger in contact |
| 0122+0743E        | 2927 ± 2          | 285 ± 5 | 69       | UGC 993E, component of major merger in contact |
| 0335–052W         | 4038 ± 2          | 64 ± 8  | 37 ± 9   | Centre between two knots, W comp. of major merger on H\(\alpha\) data |
| 0335–052E         | 4053 ± 2          | 53\(^a\) | 37       | Counter-rotation core, expanding shell, E comp. of major merger on H\(\alpha\) data |
| 0822+3542         | 727 ± 2           | 51 ± 7  | 31 ± 15  | \(H\) and \(H\)\(\alpha\) motions are decoupled |
| J1044+0353        | 3865 ± 1          | 273 ± 6 | 51       | Distorted kinematics of E-half of the disc |
| 1116+517          | 1342 ± 2          | −22 ± 7 | 50       | Lack of regular rotation, probable major merging remnant |
| 1159+545          | 3592 ± 1          | −13 ± 5 | 38       | Probable merger |
| 2236+1344N        | 6176 ± 2          | 165 ± 30| 31       | Component of major merger in contact |
| 2236+1344S        | 6164 ± 1          | 150 ± 10| 35       | Component of major merger in contact |
| J012544+075957    | 3012 ± 3          | 324 ± 7 | 64       | Companion of UGC 993 |
| 0822+3545         | 742 ± 4           | 105\(^a\) | 63\(^a\) | Companion of HS 0822+3542. |

\(^a\)Values taken from published H\(\alpha\) maps.

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some cases, the use of only Hα kinematics data can be insufficient to distinguish recent interactions from other types of kinematic disturbance. However, the combination of ionized gas kinematics with various morphology indicators, and the use of H\textsc{i} maps (when they are available), or even of integrated H\textsc{i} profiles (Conselice 2006), can lead to the correct classification.

A complementary study of a subsample of XMD galaxies with similar goals was conducted based on Giant Metrewave Radio
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Telescope (India) (GMRT) H\textsubscript{i} mapping, and the first results are presented in Ekta, Chengalur & Pustilnik (2006), Ekta et al. (2008), Chengalur et al. (2006) and Ekta et al. (2009). Some earlier results of H\textsubscript{i} mapping of XMD starbursting galaxies with Very Large Array (VLA) were presented by van Zee et al. (1998) for I Zw 18 and Pustilnik et al. (2001b) for SBS 0335–052E,W. The H\textalpha kinematics of ionized gas in the prototype XMD galaxy I Zw 18 was analysed by Petrosian et al. (1995). All these data evidence for the importance of interactions in the current starbursts of studied XMD galaxies.

If we consider the star-forming or BCGs in general, there are very few 2D studies of H\textalpha kinematics. However, for the majority of them, the morphology data indicate strong disturbances in the outer parts. For some of them, such as II Zw 40, there is clear evidence of a recent merger. Several luminous BCGs were studied

**Figure 3.** Same as in Fig. 2, but for galaxies HS 0822+3542, SDSS J1044+0353, SBS 1116+517 and SBS 1159+549.
Figure 4. Same as in Fig. 2, but for XMD galaxy HS 2236+1344 and for two by-product LSB galaxies Anon J012544+075957 and SAO 0822+3545.

by Östlin et al. (1999) via imaging in several bands and through Hα kinematics with FPI. These authors concluded that all of their galaxies are best treated as being in the stage of merging.

It is worth noting that, in such type of studies, the knowledge of the gas kinematics in the outer parts of a disc can be crucial. In particular, a good illustration is the luminous BCG Arp 212 (III Zw 102). For this galaxy, García-Lorenzo et al. (2008) obtained the ionized gas velocity field for the circumnuclear region from integral-field spectroscopy with INTEGRAL fibre-based system. From these spatial limited data, they suggested that the galaxy ‘shows a velocity field resembling a rotational system’. However, the large-scale Hα velocity field taken with FPI revealed a more complex picture where the outer H ii regions belong to a warped polar ring, formed via the external gas accretion (Moiseev 2008). We emphasize that the spatial coverage in our study for all programme galaxies, due to the large SCORPIO field of view, was sufficient to include their distant...
periphery. Thus, we do not miss any substantial gas velocity field deviations, as long as they have Hα emission above the detection threshold.

First, we discuss the analysis and model fitting of Hα for each XMD galaxy individually (along with available H I maps for some of them), and then, we summarize our conclusions for the subsample as a whole.

4.1 UGC 772 = SDSS J0113+0052

This galaxy has quite a large extent (∼1 arcmin) and very complex morphology and kinematics. Observations were obtained at rather poor seeing of ∼4 arcsec, but this was sufficient for general characterization and modelling of its velocity field. The seeing probably has somewhat affected the picture for the ‘S knot’, which has a total extent of ∼20 × 10 arcsec. The optical light, both in broad-band continuum and in Hα, shows clearly two distinct components. The larger one (or the main body) with the overall extent of ∼50 × 20 arcsec is elongated at PA ∼ 60°, and contains three H II regions, each having some elongation and/or substructure. Izotov & Thuan (2007) obtained spectra for three H II regions in the main body on one slit. Their values of O/H in all three regions are consistent to each other with the cited errors and can be treated as O/H for the whole main body. We estimated that the weighted mean for those three O/H values corresponds to 12 + log(O/H) = 7.29 ± 0.05. The general velocity gradient in the main body is along the North-South (NS) direction, that is almost perpendicular to the major axis of symmetry.

The centre of the second distinct component (hereafter UGC 772 S) is situated ∼35 arcsec (or ∼2.8 kpc at the adopted distance of 16.3 Mpc) S of the geometrical centre of the main body. This is also elongated in both continuum and Hα, roughly in the NS direction and has a clear structure. There are no published measurements of O/H for this region. Our recent spectrum of this region at the SAO 6-m telescope (Pustilnik et al. in preparation) results in 12 + log(O/H) = 7.38 ± 0.07. Despite this O/H being somewhat larger than that in the main body, the errors of both values are too large to claim a real difference. The general velocity gradient along the EW direction (about minor axis) is clearly seen in this component.

The velocity dispersion is rather low (10–20 km s$^{-1}$) in all H II regions around current SF sites, where the intensity of Hα show local peaks. The latter is common for the majority of other studied SF galaxies. It reaches values of 40–50 km s$^{-1}$ in several low-brightness small periphery knots, where this enhancement is probably related to shocks in expanding shells.

To zeroth order, the tilted-ring model is a reasonable approximation for the global motions in this object over the full range of the observed velocities. However, since the distribution of Hα emission has a huge gap between the main body and the S component, it is
difficult to find a good fit based only on our FPI data. The GMRT H\textsc{i} velocity field for this object from Ekta et al. (2008), which shows consistent features with our H\textalpha{} velocity field in the overlapping regions, is helpful for the choice of the best-fitting model. Therefore, we accepted the value of disc inclination from those H\textsc{i} maps.

The next parameters -- the systemic velocity of kinematic centre and the PA of major kinematic axis -- were derived from our H\alpha{} data. There is no well-defined photometric centre. Therefore, the rotation centre was determined only from the symmetry of the velocity field. Its position also agrees (within a few arcsec) with the centre of H\textsc{i} distribution and rotation as it follows from the GMRT data. A model was constructed only for \( r > 12 \) arcsec; since in the inner region the number of points with the measured velocities is small and we fail to construct the stable model. In the outer regions, the circular rotation model fits well the observed velocity field. The values of residual velocities in general do not exceed \( 5-10 \) km s\(^{-1}\), reaching \(| \pm 15 \) km s\(^{-1}\) in several regions. The latter are still smaller than the observed amplitude of the rotation curve (18 km s\(^{-1}\)). The largest non-random residual velocities (both negative and positive) are seen in the region of UGC 772 S. This looks like a more or less systematic gradient with the full range of \( \sim 30 \) km s\(^{-1}\).

Due to the patchy structure of ionized gas and the evident problems with a simple modelization of its global velocity field, it is important to compare the H\alpha{} velocity field with a lower resolution, but much better sampled motions of H\textsc{i} as seen, e.g. in H\textsc{i} maps obtained with GMRT in Ekta et al. (2008). In particular, as well seen in their fig. 9 (right) for the FWHM beam of \( 15 \times 10 \) arcsec, the gas velocities observed in H\textsc{i}, in both the main body and UGC 772 S, correspond well to those measured in H\alpha{}. The general direction of the H\textsc{i} velocity gradient is close to NS within the main optical body in accord with the ionized gas motions. However, one can see strong deviations of H\textsc{i} velocities near UGC 772 S (and the related H\textsc{i} density peak), and in the S part of the H\textsc{i} ‘disc’. They look like an additional, smaller velocity component with the gradient being roughly along the EW direction. The other indications on the strong tidal H\textsc{i} protrusions are seen in their map in fig. 9 (left). The H\alpha{} velocity field in UGC 772 S also shows a gradient close to the EW direction, and thus, ionized gas motions are coherent with those of H\textsc{i}. These kinematically and spatially decoupled components of UGC 772 suggest that we are witnessing a dwarf galaxy merger stage (the main body of UGC 772 and UGC 772 S), probably close to coalescence. An alternative interpretation of the region UGC 772 S as a supergiant H\textsc{ii} region on the edge of a dwarf galaxy looks quite improbable due to three facts: (i) the strong disturbance of the overall H\textsc{i} morphology, (ii) the occurrence of the galaxy’s highest H\textsc{i} density peak in the edge region is very unusual for an isolated galaxy, and (iii) the velocity field in this region is clearly detached from the main galaxy motions.

UGC 772 is situated in a small group of gas-rich galaxies (e.g. Ekta et al. 2008). Therefore, such galaxy collision looks quite probable. The current starburst in UGC 772 and in this smaller S ‘companion’ galaxy is then most probably triggered by their collision.

### 4.2 UGC 993 = HS 0122+0743

This is one more rather extended object with very complex morphology and kinematics. The body, in both continuum and H\alpha{}, represents a group of seven bright knots (SF regions) superimposed on a LSB component. They are visually joined into two aggregates of similar size. The velocity field looks rather regular with two regions of clear gradient with the same direction and sign and the velocity ranges of \( \sim 100 \) and \( \sim 60 \) km s\(^{-1}\). The regions roughly correspond to the W and E parts of the body. The velocity dispersion in most of the galaxy body, and in particular, around the SF knots, is quite low: \( \sim 10-30 \) km s\(^{-1}\). As in the previous galaxy, it is enhanced up to \( 50-60 \) km s\(^{-1}\) in several areas between H\textsc{ii} regions.

Guided by its morphology and the appearance of its velocity field, we model this object with two rotating discs in contact (see Fig. 2). The first component, on the W edge, is fitted with \( V_{sys} = 2953 \pm 2 \) km s\(^{-1}\), \( PA = 295^\circ \pm 5^\circ \) and with model-derived \( i = 37^\circ \pm 4^\circ \). Maximal rotation velocities (after inclination correction) reach \( \sim 30 \) km s\(^{-1}\). The second component, at the E edge, is best modelled with \( V_{sys} = 2927 \pm 2 \) km s\(^{-1}\), \( PA = 285^\circ \pm 3^\circ \) and \( i = 69^\circ \) (estimated from its axial ratio). For this component, the inclination corrected, maximal rotation velocity reaches \( \sim 50 \) km s\(^{-1}\). Resulting residual velocities appear rather small (\( \lesssim 8 \) km s\(^{-1}\)) in most of the mapped area. The largest positive values of residuals are seen S of the bright H\textsc{ii} region of the W component and on the NW of the E component. They may be the tracers of current interaction or outflows. The two prominent, but relatively compact regions of negative residuals (near the kinematic centre and near the SE edge) in the E component can be related to shells around recent starbursts. Or alternatively, the latter can be the tidally disturbed gas with counter-motion relative to that at the NW edge. For the case of modelling UGC 993 by a single rotating disc (as the first guess), the overall residual velocities were by a factor of 2 and more larger.

The recent H\textsc{i} maps obtained at GMRT (Ekta et al. in preparation) show clear evidence of disturbed structure, with the large low-density H\textsc{i} plume stretching to the angular distance of \( \sim 1 \) arcmin to the S of a denser H\textsc{ii} envelope that covers the optical body of the galaxy. The whole H\textsc{i} gas shows very complex kinematics. In the regions, where the H\alpha{} emission is well traced, H\textsc{i} displays the velocity pattern similar to that presented here in H\alpha{}.

All available morphology and kinematics data suggest that in UGC 993, we are witnessing a rather rare case of dwarf galaxy encounter in contact, when they have well traced regular velocity fields of both components. The kinematic data suggests that the real distance between the colliding galaxies is significantly larger, and their visible contact is due to projection effects. The strong SF activity in many H\textsc{ii} regions, presumably triggered by the recent strong interaction, is spread over the components’ bodies.

From the model fit of the observed velocity field, the deprojected rotation velocity in the E component is a factor of \( \sim 1.6 \) larger, and hence, its estimated total mass should also be significantly larger. If the Tully–Fisher scaling is valid for the two discs in collision \( (M \propto V^3) \), the E component can be \( \sim 5 \) times more massive. This would imply a case of minor merger. However, rather similar sizes of the two galaxies in question (as best followed namely through H\alpha{} velocity field) and a strong H\textsc{i} tidal plum mentioned above, are strong evidence for a major merger. The above large difference in rotation velocities can be due to two factors: (i) not properly correcting for inclination angle in the W component, (ii) the velocity fields themselves are affected by strong interactions, so the Tully–Fisher relation may not be applicable. To construct a more self-consistent model, one needs to combine both H\alpha{} and H\textsc{i} velocity fields, as well as some additional photometry including NIR data. This will be attempted in a forthcoming analysis.

### 4.3 The system SBS 0335–052E,W

The SF galaxy SBS 0335–052W is the most metal-poor gas-rich object with an O/H range in different knots between \( 6.9 < \log(O/H) < 7.22 \) (Izotov et al. 2009). With SBS 0335–052E (at 22 kpc in projection, Pustilnik et al. 2001b), it comprises a
unique pair of interacting/merging gas-rich dwarfs with the lowest metallicities. Both galaxies show unusually blue stellar population in the outer parts of their optical images (Pustilnik et al. 2004b). The ratio $M(H\!\!\!i)/L_B \sim 5$ for SBS 0335–052W is one of the greatest known. The recent detailed study of its disturbed $H\!\!\!i$ kinematics and morphology with GMRT is presented by Ekta et al. (2009). It suggests a merger of extended gas bodies soon after the first encounter. However, the denser central regions of both galaxies, with regions of current SF and surrounding ionized gas, are separated at a significant distance, and can be thus less susceptible to an external disturbance. Therefore, one can hope that kinematics of their innermost ionized gas can keep information on galaxy original rotation. Due to the recent close encounter between E and W galaxies, the gas motions are significantly affected by the tidal torques, especially in the outer parts of colliding galaxies. On the other hand, the gas kinematics in the innermost part can be affected by current/recent SF episodes.

One of the important issues in understanding this unusual interacting pair is the following: why do the optical luminosities and star formation rates (SFRs) of E and W galaxies differ by an order of magnitude, while their global $H\!\!\!i$ properties are pretty similar? In principle, the substantial part of the answer can be related to differences in the geometry of collision for two components and the related strength of tidal action. Indeed, the high-resolution GMRT maps of the innermost $H\!\!\!i$ gas give evidence for a significant difference in the main velocity gradients in E and W galaxies. For the orbital plane sky projection close to the EW direction, the collision of the E galaxy is closer to a retrograde one. Meanwhile, the innermost velocity field of the W galaxy, having its main gradient in the NS direction, corresponds to an almost polar collision. This would imply a less effective tidal perturbation. Our FPI $H\alpha$ velocity field allows a consistent check of the $H\!\!\!i$ data.

### 4.3.1 SBS 0335–052W

The observed ionized gas velocity field of the W galaxy looks like a combination of two components. One, centred at the bright $H\alpha$ region, shows a very small gradient, with an amplitude of less than $\sim 10$ km s$^{-1}$ and the direction close to NS. The other reflects the gas motion between two peaks of $H\alpha$ emission (mainly in EW direction) and has the amplitude of $\sim 20–25$ km s$^{-1}$. The ‘best-fitting’ model of rotating disc describes primarily the latter motion, which seems to be related to the tidal flows seen in $H\!\!\!i$ maps. However, the PA $\sim 70^\circ$ accounts for the former component. Thus, the $H\!\!\!i$ kinematics gives additional evidence on the presence of a velocity component roughly in NS direction, well seen in the high-resolution $H\!\!\!i$ maps. The fainter $H\alpha$ region, 3 arcsec E of the main star-forming region, is situated along the direction, which is closer to the direction of the compact $H\!\!\!i$ tidal protrusion, well seen in fig. 5 of Ekta et al. (2009). By analogy with the discussed opportunity of stimulated SF in asymmetric shells prompted by tidal outflows in the case of E galaxy (Ekta et al. 2009), the similar situation can take place for W galaxy (albeit, with smaller power).

### 4.3.2 SBS 0335–052E

The ionized gas kinematics of SBS 0335–052E were studied by Izotov et al. (2006) on the limited region of $11 \times 7$ arcsec$^2$ around the central star-forming regions. In that work, the general velocity field was not discussed. Instead, they find the two-component $H\alpha$-line profiles in several periphery regions, with component separation of $\sim 50$ km s$^{-1}$, which were treated as the appearance of fast shells.

In our observations, we constructed the $H\alpha$ velocity field in the region of $\sim 17 \times 17$ arcsec$^2$ in size.

Similar to the W component, we compare the motions of ionized gas in the E galaxy with that of $H\!\!\!i$ gas in the same region. This comparison is conducted on the GMRT $H\alpha$ maps with the angular resolutions of $\sim 20$ and 9 arcsec. Since the respective analysis was already performed in Ekta et al. (2009), this allows us to look at the observed $H\alpha$ velocities in a more general context. Namely, there are two systems in the $H\alpha$ velocity field, which are identified with gas motions in elongated tidal tails. A longer and more rarefied one is directed in approximately SW–NE direction with velocities growing to the NE edge, that is in the direction opposite to the position of the companion. A shorter, curved denser tail starts roughly in direction to NW and then bends to the W companion. For this tail (protrusion), the velocity decreases while gas travels further from the E galaxy. This direction is close to that of the asymmetric arc of ionized gas well seen in the Hubble Space Telescope (HST) $V$-band image of Thuan, Izotov & Lipovetsky (1997).

The coarse comparison of the observed $H\alpha$ velocity field in Fig. 2 with that of the described $H\!\!\!i$ one shows qualitative agreement. The region of minimal line-of-sight velocities at $\sim 6–7$ arcsec NW from the central starburst is close to the position of the arc. Thus, the effect of the expanding shell (visible as relative negative velocities on its front side) can also contribute to the structure of the velocity field. The significant swing of the isovelocity contours in the central region ($r \leq 10$ arcsec from the centre) seems may be related to the appearance of an expanding shell. To check how the disturbed velocity field looks like in the presence of a shell (in the zeroth approximation), we consider in the Appendix A several simulated velocity fields of rotating disc with a shell in different positions. The observed velocity field of SBS 0335–052E resembles that in our Model 3, which implies an off-centre location of the shell centre on the disc minor axis. Based on conclusions, obtained in Appendix A, we fixed the position angle of the model disc (PA $= 53^\circ$) in accord with the orientation of the large-scale $H\!\!\!i$ structure. This model of rotation takes into account the main component of the velocity gradient (roughly from SW to NE). In the residual map, one can clearly separate the same velocity minimum of the irregular form NW from the centre, related to the arc. The latter is natural to attribute to the approaching part of a shell, produced during a relatively recent episode of SF. Having in mind its irregular form, one can think of a superposition of two spatially close shells. Furthermore, the negative gradient in the NW direction is still visible, consistent with the similar flow seen along the $H\!\!\!i$ NW tail.

It is worth noting the unusual behaviour in the model fit of rotation velocity in the very centre of the galaxy, at $r < 2$ arcsec. This can be treated as an appearance of kinematically decoupled counter-rotation, which could be a trace of merging gaseous clouds with the specific orientations of their angular momenta. However, the observed rotation velocities are too small. Therefore, the more probable option is that this a feature of the velocity field appears due to non-circular motions produced by a shell formed near the disc centre.

The galaxy SBS 0335–052E, unlike SBS 0335–052W, shows much more active SF during the last several hundred Myr. This induces both large-scale shells/arc and increases the amplitude of chaotic (turbulent) motions. The local peculiarities of $H\alpha$ kinematics are better acquired by high-resolution spectra with VLT in Izotov et al. (2006). In particular, they detected wide-spread regions outside the central brightest clusters 1 and 2, where the line profiles are split on two components with velocity differences of $\sim 50$ km s$^{-1}$. The ‘broad’ lines with FWHM up to $\sim 100$ km s$^{-1}$ are present in...
these regions as well. While our angular resolution is about a factor of 1.7 worse, we also see in the corresponding regions the enhanced velocity dispersion of \(\sim 60–70 \text{ km s}^{-1}\), corresponding to FWHM \(\sim 150 \text{ km s}^{-1}\). Accounting for smoothing due to the worse seeing, these values look consistent. In fact, as the illustration in Fig. 1 shows, our data also hint at the two-peak structure of line profiles in the mentioned regions, but due to insufficient velocity resolution they can be treated only as an indication.

Summarizing the overall ionized gas kinematics of the E galaxy, we conclude that, in accord with H\(\alpha\) kinematics (Ekta et al. 2009), its direction of rotation is closer to the orbital plane. In general, we assume that before the merging galaxies experience coalescence, their innermost regions keep the information on their original rotation. In difference with the W galaxy case (polar collision), the collision of the E galaxy is closer to prograde or retrograde. As emphasized by Ekta et al. (2009), the latter may be one of the reasons of large differences in the current and earlier SFRs between E and W galaxies.

### 4.4 HS 0822+3542

The H\(\alpha\) velocity field for this BCG is rather well fitted by the model of flat rotating disc. The rotation velocity curve raises up to \(\sim 13 \text{ km s}^{-1}\) at the radius \(r = 3 \text{ arcsec} \sim (200 \text{ pc})\) and then falls to \(\sim 7–9 \text{ km s}^{-1}\) at radius of \(r = 5–6 \text{ arcsec}\). The region with the maximal residual velocity (of \(\sim 10 \text{ km s}^{-1}\)) is positioned at a secondary peak of H\(\alpha\) emission at \(\sim 7–8 \text{ arcsec}\) NW of the main starburst region. This could be the brightest fragment of a large loop, a probable relic of a somewhat earlier star-forming episode. The comparison of H\(\alpha\) kinematics with H\(\Pi\) morphology and kinematics (see Chengalur et al. 2006) leads to interesting conclusions. At the highest angular resolution of \(\sim 6 \text{ arcsec}\), the related H\(\Pi\) cloud is strongly elongated in the NS direction. The brightest H\(\Pi\) region is situated between two H\(\Pi\) density peaks. Due to low S/N ratio, the H\(\alpha\) velocity field is constructed only for the low-resolution data cube (beam \(\sim 23 \text{ arcsec}\)). This has a general (but small) gradient in approximately NS direction. However, in the vicinity of the optical body, one can see the swing of isovelocity line, roughly in the direction close to the PA of H\(\alpha\) velocity gradient.

The most probable reason for the formation of decoupled kinematic patterns – the internal as visible in ionized gas, and near polar orbits as outlined by H\(\Pi\) – is the interaction with a nearby LSB dwarf SAO 0822+3545. The latter is also mapped in H\(\alpha\) in the same observations and is discussed in Section 4.9. This Low Surface Brightness Dwarf (LSBD) is situated at the projected distance of 3.8 arcmin (\(\sim 15 \text{ kpc}\)) and has line-of-sight velocity of only \(\sim 15 \text{ km s}^{-1}\) larger. It is \(\sim 3\) times more massive in H\(\Pi\) and \(\sim 0.35 \text{ mag more luminous in } B\)-band than HS 0822+3542 (Pustilnik et al. 2003a; Chengalur et al. 2006). Therefore, one expects that the past interaction of the BCG progenitor with this LSBD could induce a starburst in HS 0822+3542.

Corbin et al. (2005), from their HST imaging of HS 0822+3542 with the spatial resolution of \(\sim 5 \text{ pc}\), found that its central SF region consists of two distinct components with projected separation of \(\sim 80 \text{ pc}\). Based on this morphology, they suggest that this very compact dwarf galaxy is currently being assembled from two tiny unrelated components. Their H\(\alpha\) kinematics of this BCG, in difference to several other galaxies in this study, is rather well fit by a single disc (albeit disturbed by the earlier starburst(s) and related shell(s)). This is difficult to match with the idea that the BCG is currently forming from two unrelated fragments.

It is worth noting that this H\(\alpha\) kinematics and H\(1\) data from Chengalur et al. (2006) for HS 0822+3542 do not provide a comprehensive picture of the overall gas motions. Indeed, on one hand, the regular H\(\alpha\) rotation within the whole region of optical emission (with the total extent of \(\sim 16 \text{ arcsec or } \sim 1 \text{ kpc}\)) has an amplitude of \(\sim 13 \text{ km s}^{-1}\). On the other hand, H\(1\) data shows rotation with an amplitude of less than 5 km s\(^{-1}\). At the moment, it is unclear how much the beam-smearing affects the H\(1\) velocity data.

### 4.5 SDSS J1044+0353

In the SDSS colour image, this galaxy is elongated along the EW direction, with an extent of \(\sim 10 \text{ arcsec}\). The extent along the NS direction is \(\sim 4 \text{ arcsec}\). The brightest part, the ‘comet head’ on the W edge, is very blue; while the more diffuse tail with a second, E ‘peak’ at \(\sim 4 \text{ arcsec}\) is somewhat redder. The analysis of surface brightness and colour radial dependencies by Papaderos et al. (2008) confirms this impression. They use the blue colours of a lower SB part of this object to infer the small ages of the underlying LSB disc. However, reservations are made on the possible significant contribution of nebular emission to its colour that should be accounted for. Indeed, from our rather deep H\(\alpha\) image, the extent of the galaxy nebular emission (\(\sim 12 \times 8 \text{ arcsec}\)) appears to be similar to that of the SDSS continuum images.

The two-nuclei morphology of this galaxy is similar to that of other studied objects (HS 2236+1344, SBS 1159+545), for which their H\(\alpha\) kinematics shows good evidence for a merger event. The simple disc model that best fits the observed H\(\alpha\) velocity field has the following parameters: \(V_{\text{sys}} = 3865 \pm 1 \text{ km s}^{-1}\), \(PA = 273^\circ, i = 51^\circ\). The bright rotating core is well fit by a rotation centre shifted to the E by \(\sim 0.5 \text{ arcsec}\) from the photometric centre. The maximal observed (not corrected for inclination) rotation velocity is \(8–9 \text{ km s}^{-1}\). This peak is well seen on the model rotation curve in Fig. 5 at \(r = 2 \text{ arcsec}\). The residual velocities in the ‘core’ region (\(r < 2.5 \text{ arcsec}\)) are small (\(<5 \text{ km s}^{-1}\)). In outer regions, the regular rotation falls significantly and the residual velocities amount up to \(10–15 \text{ km s}^{-1}\). The fitting by a flat disc model with the maximal rotation velocity of \(\sim 10 \text{ km s}^{-1}\) results in rather small overall residuals. However, the two outer regions of the E component show residuals of up to \(\pm 20 \text{ km s}^{-1}\). Namely, in these regions we see a maximal velocity dispersion of up to \(50 \text{ km s}^{-1}\). Besides, the radial dependence of rotation velocity is quite atypical with a substantial fall after the maximum at \(r = 2 \text{ arcsec}\). This suggests that the gas kinematics of the E half of the galaxy are significantly disturbed. On the colour SDSS image, one can also see a redder, diffuse extension S of the main elongated body. All these properties are evidence for an unrelaxed state of this galaxy.

The available data are not sufficient to make a confident conclusion on the nature of this object. At the current level of understanding of its morphology and gas kinematics, the data do not contradict an idea that this is the result of a relatively minor, almost completed merger. Other interpretations look more problematic. The E component has a significantly smaller mass than the W one, in difference with e.g. the case of HS 2236+1344. This results in a relatively weak velocity disturbance in the W component and a much fainter luminosity of E component in respect of that for W one. High-resolution H\(\pi\) mapping could probably produce a more complete picture of its dynamics during the last few hundred Myr.

### 4.6 SBS 1116+517 = Arp’s galaxy

This XMD BCG has a complex morphology in the central part, which consists of three knots with very different fluxes situated in
a region with a total extent of \( \sim 5 \) arcsec (as first noticed by Arp 1965). The outer parts also show rather irregular morphology with finger-like protrusions, in particular on the S and E edges. While the full range of line-of-sight velocities in H\(_z\) is more than 80 km s\(^{-1}\), the velocity field is rather complex. It is hard to see tracers of regular rotation. Nevertheless, we try to construct the model of rotating disc for radial distances \( r < 9 \) arcsec, which we extrapolate to the outer region. The centre of the inner isophotes was set as the centre of rotation. As one expects, the rotation is indeed small: its maximal observed line-of-sight velocities are of the order of 5–10 km s\(^{-1}\), while the residual velocities are \( \sim 20 \) km s\(^{-1}\) in the central part and reach the value of \( \sim 50 \) km s\(^{-1}\) at the E and SE periphery. The region with the most peculiar (redshifted) velocities is situated SE from the bright ‘central’ knot and possibly represents the result of a merger (or infall to the disc).

While the ‘best-fitting’ model with rotation can account for maximal rotation velocity of \( \sim 10–12 \) km s\(^{-1}\), the resulting residual velocity field shows the regions with values down to \( -20 \) km s\(^{-1}\) and up to \( +50 \) km s\(^{-1}\). This very disturbed velocity field, especially in outer parts of an ionized gas body, suggests strong perturbation. The presence of expanding shells from recent starbursts is probably one of the possible reasons. If one assigns the regions with the most negative velocities on the residual map to approaching fronts of such shells, their expansion velocities are \( \sim 20 \) km s\(^{-1}\) and the total sizes are \( \sim 3–5 \) arcsec (or \( \sim 300–500 \) pc at the adopted distance of 23 Mpc). The sizes are quite typical of ionized-gas shells, visible in similar galaxies. However, the large positive residual velocity at the E edge of the galaxy is difficult to reconcile with shells.

The morphology of H\(_z\)-emission region and velocity fields, both the observed and residual, suggests strong external disturbance. No candidate galaxy capable of producing that strong of a disturbance is visible in the BCG environment. Therefore, the most natural interpretation that emerges from the study of SBS 1116+517 morphology and gas kinematics is the recent major merger of dwarf galaxies, since for a minor merger one expects a relatively weak effect on the overall velocity field of the more massive component. If this picture is correct, one should expect that the H\(_i\) morphology and velocity field are highly disturbed. Thus, this galaxy requires follow-up H\(_i\) mapping with angular resolution of \( 3–5 \) arcsec.

### 4.7 SBS 1159+545

On the SDSS image SBS 1159+545 consists of two very blue knots (separated by \( \sim 5 \) arcsec, or \( \sim 1.3 \) kpc at the adopted distance of 52.5 Mpc), elongated roughly along NE–SW direction, with the luminosity difference of a factor of \( \sim 2 \). There are also redder lower brightness fragments; one is situated between the two blue knots and the other, with the total extent of \( \sim 5 \) arcsec, stretches as a tail of the fainter, blue SW knot. The SW knot itself has an extended structure, roughly oriented along EW, and its redder tail looks like a continuation of this blue knot. On the other hand, the brighter NE knot also looks elongated on our narrow red continuum image, in a direction of SN. This overall complex, curved morphology indicates a non-equilibrium state of this object.

The full range of H\(_z\) velocities seen in our data is \( \sim 40 \) km s\(^{-1}\). The velocity field is complex, and does not resemble a projected rotation. Moreover, it resembles that of some other objects in this study, with ‘two-nuclei’ morphology, which we have argued are mergers close to the full coalescence (SDSS J1044+0353 and HS 2236+1344). Namely, there are two local maxima in the line-of-sight velocity, close to the positions of the H\(_z\)-emission peaks and a clear minimum along the border, or ‘middle’ lane, between these SF knots. From the position of this middle lane, the observed velocities grow to both NE and SW directions. However, after reaching the local maxima near the H\(_z\) emission peaks, they again fall. The largest velocities are seen on the W and E edges of the NE knot as well as at similar outer parts of the SW knot.

The velocity field model was built for the range \( r < 9 \) arcsec (with the centre at the NE knot) and was extrapolated to the SW knot. The ‘best-fitting’ model for the flat rotating disc centred on the brighter NE knot can account for only an amplitude of \( \sim 8 \) km s\(^{-1}\) along the line of sight. The residual velocities are significantly larger, amounting on the knot’s E edge of \( 15–20 \) km s\(^{-1}\). Similar indications of an overdisturbed velocity field come from the map of velocity dispersion. While in the regions around bright knots, this parameter does not exceed \( 15–20 \) km s\(^{-1}\). In the E part of NE knot and the W part of the SW knot, this exceeds \( 30–50 \) km s\(^{-1}\). The PA = \( -13^\circ \) of the ‘best-fitting’ kinematic model significantly differs from PA \( \approx 30^\circ \) of the apparent ‘disc’ plane – if the two knots were in regions in the same disc galaxy. But this is consistent with the orientation of the NE knot itself, as seen from our narrow-band continuum image. An attempt to interpret the whole velocity field as a result of combination of two expanding shells does not work. In this model, it is difficult to understand how the gas in the middle lane acquired its low observed velocity, while the line-of-sight velocities in the directions of expected centres of shells (NE and SW knots) show local maxima. Summarizing this velocity field analysis, we suggest that from both the BCG morphology and gas velocity field, the most plausible interpretation of the data is the merger of two dwarf galaxies.

#### 4.8 HS 2236+1344

This XMD BCG also has the two-nuclei morphology with disturbed outer parts (Fig. 4). The separation of two bright knots, oriented in the NS direction, is \( \sim 3 \) arcsec (or \( \sim 1.2 \) kpc in projection at the adopted distance of 85 Mpc). As seen in deep images (not shown here), the latter includes small tails protruding from both the N edge of the N component (to the W) and from the S part of the S component (Pustilnik et al. in preparation). These features already hint on the tidal perturbations in both components. Pramskij et al. (2003) studied the H\(_z\) velocity field of this object with a long slit, positioned along the NS direction. They discovered in the position-velocity diagram that the line-of-sight velocity makes a jump in the middle between the two knots. Our H\(_z\) velocity field confirms that finding and adds important new features, including high-velocity dispersion and large residual velocities near the regions of current starbursts for any model of single rotating disc.

The total velocity range is \( \sim 45 \) km s\(^{-1}\). We attempted to fit the whole observed velocity field with the model of single flat rotating disc. Two variants of the circular motion model were constructed: (i) rotation centre coincides with the brighter (S) knot; (ii) rotation centre is fixed in the middle between N and S knots. However, both variants fail to reproduce the observed velocity gradients. For an alternative approach, the approximation of the overall H\(_z\) velocity field by two rotating discs, positioned near the centres of S and N knots, gives a good fit with maximal rotation velocities of \( \sim 25 \) km s\(^{-1}\) in both components (see Table 3 and Figs 4 and 5). These discs have close PA, \( V_{sys}, i \) and maximal \( V_{rot} \).

Due to lack of space, we focus on the model with two discs which provides a better fit to the observations than either single disc model. The map of velocity dispersion shows this parameter to be rather large in this BCG. Even its minimal values, located in the regions of both bright knots, are of \( \sim 25 \) km s\(^{-1}\). In the adjacent regions,
this parameter raises till 35–40 km s\(^{-1}\), while in the outer parts, the velocity dispersion exceeds 50 km s\(^{-1}\). The observed kinematics can not be explained as well by giant ionized shells in a single rotating disc. The latter are commonly expected to show negative relative velocities in their front edges, that is near the centres of star-forming regions, while the observed residuals are positive.

Taking into account all available morphological and kinematics data on this BCG, we conclude that the most likely nature of this object is a close strongly interacting pair of dwarf galaxies with comparable masses. It is quite probable that this pair is in the stage of merger close to full coalescence. This also provides a natural interpretation of the starbursts in both components. Indeed, as summarized by Begum et al. (2008), the late-type quiet dwarfs with that low \(\sigma\) have typical \(M_8\) in the range of \(-12.5\) to \(-14.9\). Therefore, the \(M_8 = -16.9\) for HS 2236+1344 indicates a very strong starburst.

4.9 Properties of two by-product LSB galaxies

In this section, we briefly discuss two galaxies that appeared sufficiently close on spatial and velocity separation to the main studied XMD galaxy and were mapped along with the main target.

4.9.1 Anon J012544+075957

In the FPI data cube for UGC 993, an LSB dwarf galaxy Anon J012544+075957 appeared (see bottom of Table 2) at 2.5 arcmin E and ~40 arcsec N from the main target (~29 kpc in projection). Its line-of-sight velocity (as found here from its H\(\alpha\) velocity field) is ~70 km s\(^{-1}\) larger than the mean velocity of the UGC 993 system. Its H\(\alpha\) image (Fig. 4) displays three main regions elongated roughly from NE to SW, forming the main body with the total extent of ~25 arcsec and a separate faint knot SW from this. The velocity range along the body is ~70 km s\(^{-1}\). The ‘best-fitting’ model parameters for a rotating thin disc are as follows: \(V_{\text{sys}} = 3012\ \text{km s}^{-1}\), \(PA = 324^\circ, i = 64^\circ\). The resulting rotation curve reaches a maximum value of ~25 km s\(^{-1}\) (Fig. 5) at the edge of the H\(\alpha\) map (r ~ 12 arcsec). The gas morphology of this LSB galaxy is clearly disturbed and elongated nearly perpendicular to the plane of rotation. It is interesting that in the blue continuum, the galaxy looks less elongated than in H\(\alpha\). However, there are two extensions approximately to the N and S, close to the elongation of H\(\alpha\) emission. The velocity dispersion near the peaks of H\(\alpha\) emission is a modest ~25 km s\(^{-1}\). In some of the outer regions, it rises up to 60-70 km s\(^{-1}\), but this is probably attributed to a low S/N.

Along with the already discussed two kinematically decoupled components of UGC 993, this dwarf Irr galaxy likely comprises a progenitor triplet of low-mass galaxies, whose common dynamical evolution resulted in a recent merger, as seen in UGC 993. The general problem of such dwarf bound systems was addressed, in particular, in Tully et al. (2006).

4.9.2 SAO 0822+3545

Another by-product object, SAO 0822+3545, the LSB dwarf galaxy, known as a companion of HS 0822+3542, was already discussed in Pustilnik et al. (2003a). Its unusually blue BVR colours imply a rather small age for its main stellar population. Low level SF in this LSBD was noted in the latter study based on the detection of a low EW H\(\alpha\) emission in the long-slit spectrum taken along the major axis. The new data show the 2D distribution of H\(\alpha\) emission (see Fig. 4) and allow us to perform a more careful analysis of SF issues.

In particular, our H\(\alpha\) image shows that the current SF in this LSB dwarf is highly inhomogeneous. It is concentrated in two close H\(\alpha\) regions No. 1 and 2 (~4 arcsec or ~0.26 kpc in between) at the N edge of the main galaxy body, where no light concentration is seen in the broad-band continuum images. A fainter H\(\alpha\) protrusion is seen in the W part of the faint irregular structure. The H\(\alpha\) kinematics are complex. On one hand, due to very limited spatial coverage of H\(\alpha\) emission over the LSBD body, it is difficult to derive the parameters of a rotating disc model based only on H\(\alpha\) data. On the other hand, the H\(\alpha\) velocities are in good agreement in the overlapping regions with those observed in H\(\text{I}\) as presented in Chengalur et al. (2006). Based on this fact, we fixed the position of the rotation centre, PA, and \(i\), as they emerge from the mentioned H\(\text{I}\) maps.

As usual, the velocity dispersion near the brightest H\(\alpha\) knots is rather low: ~5-15 km s\(^{-1}\). In several regions outside these two knots, where H\(\alpha\) is still seen – at ~4 arcsec SE of knot No. 1 and in the W protrusion – the velocity dispersion is large, up to 60–70 km s\(^{-1}\). This could be evidence of recent strong disturbances of the galaxy’s interstellar medium (ISM). We also note that the total H\(\alpha\) flux in this LSB galaxy is ~25 times smaller than that in its companion BCG HS 0822+3542, while its total blue luminosity is ~30 per cent higher (Pustilnik et al. 2003a). This seemingly reflects the difference between the SF properties in the two interacting galaxies, related to the difference in their density distribution and the strength of the tidal trigger.

5 SUMMARY

Summarizing the results and discussion above, we draw the following conclusions.

(i) The ionized gas kinematics in very low-metallicity star-forming galaxies, studied with FPI H\(\alpha\) observations are significantly disturbed and rarely can be well fitted by only single disc with regular rotation.

(ii) Several of our galaxies show more or less clear evidence from morphology and H\(\alpha\) velocity fields for various stages of mergers (UGC 993, SDSS J1044+0353, SBS 1116+517, SBS 1159+545, HS 2236+1344). In two cases, we have good evidence for two independently rotating discs (UGC 993 and HS 2236+1344).

(iii) In the other galaxies, the rotation component of the overall velocity field is important, but large disturbances appear. The residuals of the ‘best-fitting’ rotation model imply either a recent merger, or sufficiently strong disturbance by nearby galaxies (HS 0822+3542 and UGC 772).

(iv) Probable starburst-induced shells were identified in several galaxies (UGC 772, UGC 993, SBS 0335–052E, SBS 1116+517) through their ionized gas velocity fields and velocity dispersion maps. We presented the results of simple simulations of the expected velocity patterns which one can observe in dwarf galaxies with expanding shells. To first order, this allowed a feel for the effect of shells on the results of the tilted-ring model.

(v) The interacting/merging nature of the binary system of the well separated XMD galaxies SBS 0335–052E and W is best evident from their H\(\text{I}\) morphology and kinematics data. Despite a relatively large mutual distance, the tidal action of each component to the other clearly affects the gas dynamics of these very gas-rich objects and triggers the current SF burst and very likely the previous major SF episode (as emphasized by Ekta et al. 2009). To understand this unique interacting system (a nice representative of high-redshift
young galaxies) in more detail, one needs a wide grid of models of interacting gas-rich galaxies, like e.g. ‘Identikit’ (Barnes & Hibbard 2009), but including SF processes.

(vi) The Hα images and velocity fields for two LSB dwarfs, Anon J012544+075957 and SAO 08222+3545, companions of two programme XMD galaxies, are obtained and analysed. They can be used in statistical studies of SF in LSB dwarfs. The SF in SAO 08222+3545 is highly asymmetric and takes place mainly in two knots at the N edge, that is likely induced by the recent interaction with the nearby XMD BCG HS 08222+3542.

The statistics of XMD starbursting galaxies, for which kinematics of gas were studied in detail, is still insufficient. Nevertheless, the results of our FPI study of the ionized gas kinematics in the subsample of nine XMD star-forming galaxies, along with the complementary results of the GMRT H1 study of a part of these and other XMD galaxies (Ekta et al. 2008, 2009; Ekta & Chengalur 2010), indicate that strong interactions and mergers of very metal-poor dwarf galaxies are one of the major or significant factors triggering their current and recent starbursts. In particular, this is valid for the six most metal-poor (12 + log(O/H) < 7.30) dwarf starbursting galaxies. Merger-induced starbursts are consistent with the idea that the progenitors of such rare objects either are old and have been evolving very slowly on the cosmological time-scale before the current starburst have occurred, or they are extremely metal-poor because they are comparatively young, and thus began their SF and chemical enrichment with large delay.

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APPENDIX A: ON THE VELOCITY FIELD OF DISC WITH SUPERIMPOSED SHELL

The tilted-ring fit is very popular for analysis of gas velocity fields in galactic discs [see Teuben (2002) for detailed review]. In this approach, it is easy to connect the radial trends of kinematically determined PA and i with real changes of disc geometrical parameters (warp, polar rings, etc.) and/or with regular non-circular motions caused by spiral arms or bar. However, in dwarf galaxies the SF-induced expanding shells can significantly disturb the disc velocity field since the amplitude of the rotation curve is rather small and the size of a shell can be comparable with the size of the disc. If we allow for variations of kinematical PA with radius, it can lead to a mistaken conclusion on disc orientation or about the character of non-circular motions. In this Appendix, we examine the effect of expanding shells on the tilted-ring fitting of artificial velocity fields. The ‘observed’ velocities in our two-component model are simply the sum of line-of-sight velocities for the disc and the shell:

\[ V_{\text{obs}} = V_{\text{disc}} + V_{\text{shell}} = V_{\text{sys}} + V_{\text{rot}} \cos \psi \sin i + V_{\text{exp}}. \]  

(A1)

This approximation assumes the equal contribution of both components in the total velocity pattern in the overlapping regions, i.e. the same brightness of the components in each point. Of course, this is not similar to the real situation. However, we believe that equation (A1) can be used as a first approximation. One of the constraints used in the models below is that \( V_{\text{shell}} \) should not exceed the typical FWHM of the observed emission lines (about 30–50 km s\(^{-1}\)). Otherwise, we would detect the two-component line profiles.

The azimuthal angle in the plane of galaxy \( \psi \) is connected with the position angle in the sky by the relation: \( \tan \varphi = \tan(\text{PA} - \text{PA}_0)/\cos i \). The rising rotation curve is constructed by the relation:

\[ V_{\text{rot}} = \frac{2}{\pi} V_{\text{max}} \arctan \frac{R}{h}, \]  

(A2)

with \( h = 1 \) arcsec and the maximal velocity \( V_{\text{max}} = 30 \) km s\(^{-1}\) which is typical of dwarf galaxies in our sample.

For the shell, we use a model of a thin expanding hemisphere. This implies that we see only its approaching (blueshifted) side, whereas the redshifted one is obscured by an interior extinction. The model for the shell is

\[ V_{\text{shell}} = -V_{\text{exp}} \sqrt{1 + \frac{(x - x_s)^2 + (y - y_s)^2}{R_s^2}}. \]  

(A3)

Here, \( x_s \) and \( y_s \) are sky-plane coordinates of the shell centre relative to the disc centre. The shell has a radius of \( R_s = 3.5 \) arcsec and the expansion velocity of \( V_{\text{exp}} = 15 \) km s\(^{-1}\).

Using equation (A1), we created models for moderately inclined disc (\( i = 45^\circ \), \( \text{PA}_0 = 45^\circ \)) with the maximal radius of 10 arcsec and with various values of \( x_s \) and \( y_s \). A systemic velocity of \( V_{\text{sys}} = 1000 \) km s\(^{-1}\) was adopted, that is representative of our sample. Its value has no effect on model isovelocity patterns.

The models were calculated on the grid with cell size 0.1 arcsec. Then, the constructed models were convolved with the 2D Gaussian with FWHM = 1.5 arcsec that simulated the typical seeing effect, and were rebinned with the pixel size of 0.5 arcsec in accord with our observational conditions. Fig. A1 shows examples of typical simulated velocity fields. Figs A1 and A2 are available in colour in the online version of this article.

Model 0 represents the disc without shell. In Model 1, the shell is located in the disc centre. In Models 2 and 3, the centre of the shell is shifted along the major and the minor axes, respectively. In Model 4, the shell centre is shifted in the direction of \( \text{PA} = 180^\circ \).

The simulated velocity fields were analysed with the same tilted-ring model method under two approximations. Method I allows for radial variations of \( \text{PA} \) and \( V_{\text{sys}} \), while in Method II these values were fixed and only the rotation velocity was a free parameter. The inclination angle and the rotation centre were fixed in both methods. Fig. A1 shows the residual velocities in the both approximations. The results of fitting are shown in Fig. A2. These figures demonstrate how an expanding shell affects the observed velocity field and changes the estimates of best-fitting parameters. Namely, the central location of the shell or its offset along the disc major axis provokes the radial variations of \( V_{\text{sys}} \) (see Models 1 and 2). The shell location beyond the disc major axis also gives the systematic errors in the PA estimations (Models 3 and 4). When the shell centre lies on the minor axis, the radial trend of \( \text{PA} \) reach the maximal amplitude (~20° in our simulations). That large variation of \( \text{PA} \) can result in erroneous conclusions concerning the disc structure, like the presence of the inner warp or even of a nuclear disc.

The residual velocities in the case of Method I seem spread over a larger portion of the disc than the real area of the shell (Fig. A1). The residuals are relatively small, usually about \( \pm 5-7 \) km s\(^{-1}\). Moreover, the peak of negative (“blue”) residuals usually does not coincide with the centre of the shell. In contrast, if \( \text{PA} \) and \( V_{\text{sys}} \) are constant (i.e. for Method II), the residual velocities pattern is in a good agreement.
Figure A1. The simulated maps. (a) The relative position of the disc (grey) and shell (dark). (b) The simulated velocity field (after the subtraction of $V_{\text{sys}} = 1000\,\text{km}\,\text{s}^{-1}$). (c) The residual velocity field after the subtraction of the tilted-ring model (Method I) which allows variations of PA and $V_{\text{sys}}$. (d) The same residual field, but for Method II (PA, $V_{\text{sys}} = \text{const}$).

Figure A2. The fitting parameters for the simulated velocity fields: rotation velocity (top), position angle (middle) and systemic velocity (bottom). Blue points and red diamonds show results for Method I and Method II, respectively (colour in online version of this article).

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with the location of the shell, and the value of the negative residuals is consistent with $V_{exp}$, with except of the special case of Model 2.

It is worth noting that the rotation curve derived from the simulated velocity field can be distorted independently of the analysis method, as can be seen for $V_{exp}$ plots for Models 2 and 4 in Fig. A2. However, in the Method II approach, we can unambiguously recognize from the residual map the perturbed portion of the disc and then derive the real rotation curve on the second iteration after masking the shell region. The latter is impossible if PA and $V_{sys}$ are free parameters of the fitting, because in this case it is difficult to recognize the shell location.

Based on the results presented above, we have analysed the velocity fields of dwarf galaxies using the ‘tilted-ring’ fitting assuming that PA and $V_{sys}$ are constant with radius. When the first approximation was done, we masked the regions with large residuals (usually, larger than 5–10 km s$^{-1}$) and repeated the fitting. The final model velocity field and the rotation curve, i.e. parameters of the disc orientation were calculated after several such iterations.