

Sites of Star Formation in Tidal Structures

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Abstract. We give a short review of the current results of studying of star formation sites observed beyond the main discs of galaxies in different interacting systems: Arp 270, Arp 194, Arp 305, NGC 4656 and NGC 90. The observations were carried out at the 6-meter telescope BTA in SAO RAS with the SCOPRPIO-2 spectrograph. The properties of star forming islands, their mass, dynamics, chemical abundances, their possible fate and the mechanisms inspiring star formation, appear to be different in different systems.

Keywords: galaxies: interactions; galaxies: evolution; galaxies: star formation

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1 Introduction

A tight interaction of gas-rich galaxies is often accompanied by the formation of star-forming regions outside galactic discs or at their distant peripheries, in the local areas of the enhanced density of gas. Dynamical properties, a volume density or a chemical abundance of gas in these star forming islands may differ significantly from those observed in spiral arms of galaxies. The mechanism of their formation is an open question. A study of foci of star formation in tidal structures is important for understanding the conditions leading to the birth of stars and the evolution of young stellar complexes beyond stellar discs.

A gas associated with star formation in tidal structures, was torn away from parent galaxies, in some cases along with the disc stars. The average density of the ejected gas should inevitably be very low, and the presence of the local dense regions giving birth to stars can be attributed either to the self-gravity of gas with a low velocity dispersion in a tidal tail, or with the processes of interaction of the expelled gas with the gas environment (a static or dynamic pressure).

A fate of star-forming islands outside the discs is also not clear. They have a high chance of falling back into a parent galaxy, but in some cases they may remain as long-lived tidal dwarfs. The distinguishing properties of tidal dwarfs should be a low, if any, content of dark matter, and the moderate gas metallicity, because they consist of gas ejected from the peripheral regions of discs of more massive parent galaxies.

Below we give a short presentation of the main results of study of several interacting systems obtained in the frame of observational program which is carrying out by participants from SAI MSU and SAO RAS. All spectral observations were performed in the prime focus of the Russian 6-m telescope with SCORPIO-2 spectrograph (Afanasiev & Moiseev 2011) in the long slit mode. In every case a slit was chosen to cross the star-forming regions. We analyzed a distribution of line-of-sight velocity for different spectral lines along a slit, together with flux ratios of emission lines and the gas metallicity estimated by different methods. A special attention was paid to the excitation mechanism of emission (a classical HII region or a diffuse ionized gas (DIG)). Using a photometric data, we also tried to estimate the age and the history of star formation in the local star-forming islands.

A more detailed description of observations, a procedure of data processing, and the results of investigations of concrete galaxies one may find in the following papers: Zasov et al. (2015, 2016, 2017, 2018, 2019, 2020).

2 System Arp 270

Arp 270 = NGC 3395/96 is a tightly interacting pair of galaxies of comparable luminosity: a spiral galaxy NGC 3395 and irregular galaxy (Irr or Sm) NGC 3396, strongly inclined to the line of sight. The relative motion of galaxies seems to occur in a plane perpendicular to the line of sight, because their central systemic velocities nearly coincide. There are numerous separate islands of star formation beyond the main body of galaxies. The most notable of them is the oblong emission region of about one kpc-size between galaxies.

We measured the line-of-sight velocities of gas and stars and chemical abundances distributions along the two slits crossing the peripheral regions of galaxies (Fig.1). Irregular velocity distribution and a high velocity dispersion of emitting gas exceeding 50 km/s give evidence of the local non-circular gas flows within a scale of about 1 kpc. There is a steep velocity gradient in the region between galaxies accompanied by gradual grow of velocity dispersion of gas to the periphery of galactic discs – most probably as the result of direct collision of peripheral gaseous systems of two galaxies. Note that the brightest emission region look-

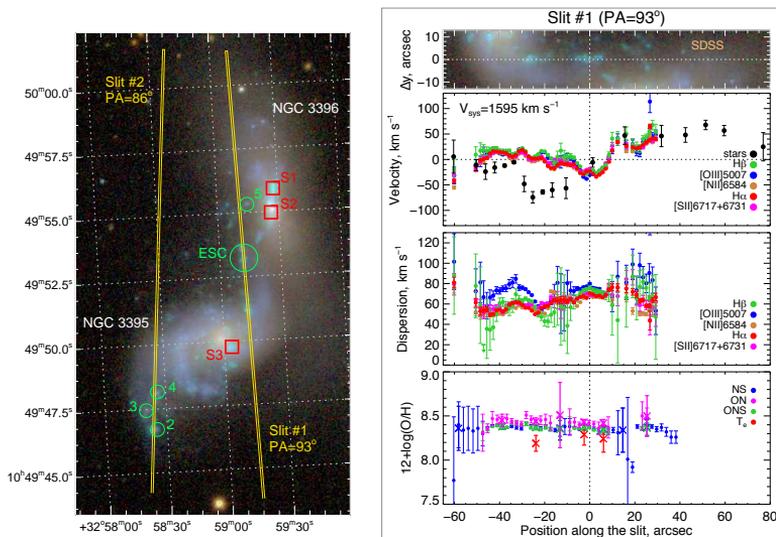


Fig. 1. Right: positions of the slits overlotted on the g,r,i SDSS image of Arp 270. Left: the profiles along a slit of stellar and ionized gas kinematics and oxygen abundance of Arp 270 for PA=93.

ing as the isolated site of star formation, lies at the beginning of the transition region between galaxies.

The main feature of the oxygen abundance distribution is the absence of significant gradients of the ratios (O/H) along the slits estimated by different methods. It evidences the efficient gas mixing which may be a result of previous convergence(s) of galaxies.

A comparison of colour indices (ugr) of several discrete sites of star formation beyond the inner regions of the galaxies estimated from the SDSS data using Starburst99 models of stellar evolution confirmed the young age ($T \leq 10^7$ yr) of stellar population without the noticeable substrate of the old population. The extended kpc-size island of star formation mentioned above does not stand out by its kinematics or abundances, so it hardly may be considered as the tidal dwarf candidate (hereafter TDG). Its location at the beginning of transition zone between galaxies allows us to propose that its formation is the result of compression of colliding gas flows of galaxies in contact.

3 System Arp 194

Arp 194 is a system of recently collided galaxies, where the southern galaxy (S) passed through the gaseous disc of the northern galaxy (N) which in turn consists of two close components (Fig.2). This system is of special interest due to the presence of regions of active star-formation in the bridge between galaxies, the brightest of which (the region A) has a size of at least 4 kpc. We obtained three spectral slices of the system for different slit positions and estimated the radial distribution of line-of-sight velocity and velocity dispersion as well as the intensities of emission lines and oxygen abundance $12 + \log(\text{O}/\text{H})$. A gas in the bridge is only partially mixed chemically and spatially: we observe the O/H gradient along the galactocentric distances both from the centers of S and N galaxies, and a high dispersion of O/H in the outskirts of N-galaxy. Velocity dispersion of the emission-line gas has the lowest values in the star-forming sites in the bridge and exceeds 50-70 km/s in the disturbed region where there are no bright extended star-forming regions, and, judging from the line ratios, the emission belongs to a diffuse ionized gas, with collisional mechanism of excitation of atoms.

Based on the comparison of stellar evolutionary models with the SDSS photometrical data, and using our kinematical profiles, we measured the ages and masses of stars and the dynamical masses of individual foci of star formation. We confirm that the largest emission island (region A) is most probably a gravitationally bound TDG with the age of $10^7 - 10^8$ yr. There is no evidence of the significant amount of dark matter in this dwarf galaxy. The measured velocities of gas along the slits crossing TDG agree with the scenario where this young star-forming island and its surrounding gas falls into the disc of S-galaxy.

4 System Arp 305

Arp 305 is a small group of galaxies dominated by the wide pair of interacting spiral galaxies of moderate luminosity: NGC 4016 and NGC 4017. For the adopted distance 50 Mpc the projected separation of galaxies is 86 kpc. The largest concentration of HI between galaxies coincides with the optical chain of blue knots of total magnitude $B \approx 17$, immersed in a faint haze, most clearly visible in UV (see Sengupta et al. 2017). It is located about halfway between the galaxies and stretched along the line connecting them at least at 7 kpc. This object is considered as the TDG candidate. Simple Stellar Population models applied to the photometric data demonstrated that the separate clumps have a very small age, which allows to conclude that this observed stellar island was recently formed from the local concentration of gas in the tidal tail.

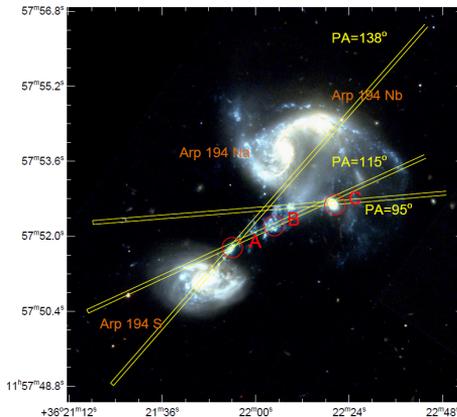


Fig. 2. The HST composite colour image of Arp 194 in BVI bands with overplotted positions of the slits.

This object was observed with the slit position shown at composite g,r,i -image in Fig. 3. We found that gas velocities in TDG are more disturbed than in the adjacent regions. At the same time, we observed neither noticeable rotation nor expansion of TDG: mean velocities of its two brightest clumps differ by no more than 20 km/s. The oxygen abundance of TDG found by izi (Blanc et al. 2015) and O3N2 (Marino et al. 2013) methods is 8.1 – 8.3, which is too high for its absolute magnitude $M_B \sim -16$ mag.

The rough estimate of dynamical mass ($M_{dyn} = (2 \pm 1) \cdot 10^9 M_\odot$) of TDG is much higher than its stellar mass, however it is comparable with the observed mass of HI connected with it. The fate of the TDG in Arp 305 seems similar to that of the stellar island in Arp 194 discussed above – it will be soon accreted by the parent galaxy.

A column gas density in the tidal bridge is maximal in the region of TDG, reaching 4×10^{20} g cm $^{-2}$ (see Sengupta et al. 2017). A rough estimate of Jeans mass for the observed velocity dispersion of gas is about $6 \cdot 10^8 M_\odot$, which agrees with the total (mostly gaseous) mass of TDG, as it is expected if the mass of TDG is close to that required for gravitational bounding. Note however that the free-fall time for this density is too long – about 10^8 yr, being comparable to the time of dynamic evolution of the perturbed galaxies. Hence, either a gas which fills TDG was inhomogeneous initially, or the current star formation was triggered by some external pressure.

5 UV Satellite of NGC 4656

The unusual dwarf low surface brightness galaxy NGC 4656UV is a close satellite of the edge-on galaxy NGC 4656. It is barely visible in the SDSS image, however it has the enhanced brightness in the UV range. Multiwavelength data analysis carried out by Schechtman-Rook & Hess (2012) led these authors to the conclusions that NGC 4656UV is a low-metallicity TDG candidate whose major burst of star formation occurred within the last $\sim 260\text{-}290$ Myr.

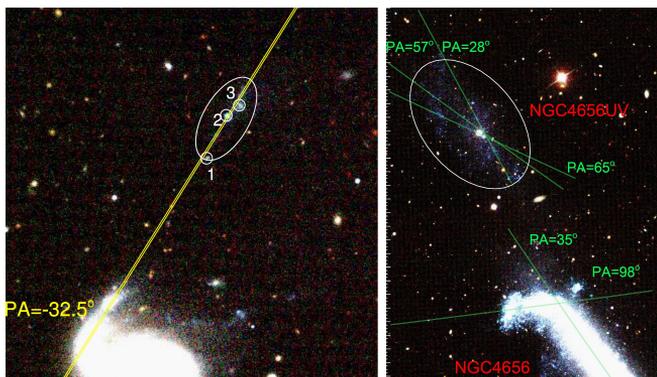


Fig. 3. The positions of the slits overplotted on the g,r,i -band image of Arp 305 (right) and NGC 4656 (left).

We did several spectral cuts across both galaxies (see Fig.3, right panel) to obtain the kinematical parameters and gas-phase metallicity of NGC 4656UV and NGC 4656. Our estimates of emission gas velocities of NGC 4656UV parallel with photometrical and HI data speak in favour of this system to be a dark matter-dominated gravitationally bound axisymmetric galaxy with the dynamic mass of about $2 \cdot 10^9$ solar masses, rather than a tidal dwarf candidate. It has quite axisymmetric exponential disc with the low central surface brightness $(\mu_0)_r = 24.1$ mag/arcsec² and the radial scale length of about 2 kpc. The parameters of NGC 4656UV are close to that observed for separate ultra-diffuse galaxies.

Oxygen gas-phase abundances found for the brightest HII-region of the UV dwarf, as well as for the emission gas of the main galaxy NGC 4656 at the side facing UV dwarf, are equally low: $12 + \log \text{O}/\text{H} = 7.8 - 8.1$ (*izi*-method). Both the low abundance and non-circular gas motions in NGC 4656 parallel with the observed young stellar population of NGC 4656UV give evidences of

the current accretion of metal-poor gas on the discs of these galaxies due to tidal interaction between NGC4656 and NGC4631. Gas flows between these two galaxies are clearly seen at the HI map of the interacting system (Rand 1994). A current star formation induced by the accreted gas may explain the enhanced UV brightness of the ‘ghost’ LSB-galaxy, which would be nearly invisible otherwise.

6 NGC 90, a Member of Arp 65 System

A peculiar galaxy NGC 90 is a pair member of interacting system Arp 65 (NGC 90/93), where both galaxies have a comparable luminosity. NGC 90 possesses a pair of unusually thin and regular inner spiral arms of Grand Design type which straighten at the periphery, passing into the short tidal tails. Curiously, the line-of-sight (LOS) velocities of the paired galaxies differ by more than 400 km/s. Such velocity discrepancy is unusually high for interacting galaxies with tidal structures. Both galaxies are the members of a group SRGb063 where X-ray gas was detected (Mahdavi & Geller 2004).

Sengupta et al. (2015) found that about a half of hydrogen mass of NGC 90 looks strongly displaced with respect to its main body – both in space and in the velocity field. High-speed gas looks like a giant non-rotating massive HI cloud, comparable with the optical galaxy by its size, which is projected on the SE part of the disc of NGC 90. The LOS velocity of this HI cloud does not agree with the velocity of the galaxy, exceeding its central velocity at about 340 km/s, so the cloud may hardly be gravitationally linked with the galaxy. It makes this system very interesting for further investigation.

We fulfilled two parallel spectral cuts with the orientations of both slits in the NW-SE direction. One of them crossed the centre of the galaxy, and another one was directed along the northern spiral arm. The first cut also run through the position of high velocity HI cloud. The most interesting result is that we found the emission patches beyond spiral galaxy, in the area of this peculiar cloud (see Fig.4). Their velocities change along the slit, increasing up to the values corresponding to that for HI cloud. It means that there exists a chain of HII regions between the galaxy and the cloud, and there are local regions of star formation which evidently are detached from the galaxy disc.

We argue that what we observe in this galaxy is similar to the HI + H_α tails of so-called jelly-fish galaxies (as an example, see Ramatsoku et al. 2019). In this case it is a ram pressure of the intra-group hot gas which is responsible for sweeping gas out of the disc.

Indeed, the difference between the observed velocity of NGC 90 and the mean velocity of the group which it belongs to, is as high as 570 km/s. The gaseous tail formed as the result of sweeping of gas, is apparently elongated along the line

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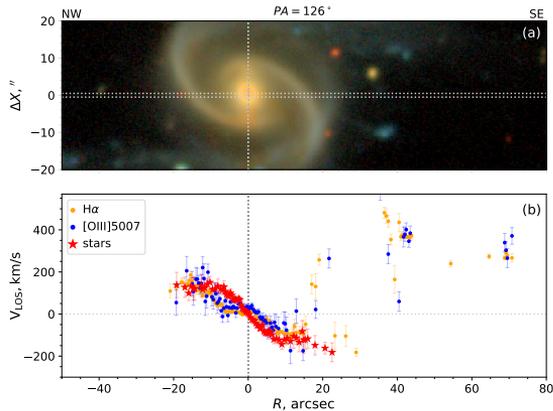


Fig. 4. Profiles of stellar and ionized gas velocities for NGC 90 along the slit passing through its center and the HI cloud observed to the right of the galaxy.

of sight, which creates the illusion of a cloud with a high column density of gas projecting onto the galaxy region. Local emission regions we found in this tail evidences that star formation beyond galaxy disc, inspired by the ram pressure of gas, has not completely faded yet.

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