

H α Velocity Fields and Galaxy Interaction in the Quartet of Galaxies NGC 7769, 7770, 7771 and 7771A

A. A. Yeghiazaryan, T. A. Nazaryan* & A. A. Hakobyan[†]

Byurakan Astrophysical Observatory, 0213 Byurakan, Aragatsotn Province, Armenia.

*e-mail: *nazaryan@bao.sci.am*

[†]hakobyan@bao.sci.am

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Abstract. The quartet of galaxies NGC 7769, 7770, 7771 and 7771A is a system of interacting galaxies. Close interaction between galaxies caused characteristic morphological features: tidal arms and bars, as well as an induced star formation. In this study, we performed the Fabry–Perot scanning interferometry of the system in H α line and studied the velocity fields of the galaxies. We found that the rotation curve of NGC 7769 is weakly distorted. The rotation curve of NGC 7771 is strongly distorted with the tidal arms caused by direct flyby of NGC 7769 and flyby of a smaller neighbor NGC 7770. The rotation curve of NGC 7770 is significantly skewed because of the interaction with the much massive NGC 7771. The rotation curves and morphological disturbances suggest that the NGC 7769 and NGC 7771 have passed the first pericenter stage, however, probably the second encounter has not happened yet. Profiles of surface brightness of NGC 7769 have a characteristic break, and profiles of color indices have a minimum at a radius of intensive star formation induced by the interaction with NGC 7771.

Key words. Galaxies: interactions—galaxies: star formation—galaxies: peculiar—galaxies: individual: NGC 7769, NGC 7770, NGC 7771, NGC 7771A—supernovae: individual: 2003hg.

1. Introduction

More than 30 years ago, NGC 7769, 7770 and 7771 galaxies, among the few hundreds of others, were included in the list of galaxies with ultraviolet (UV) excess with numbers Kaz 346, 347 and 348 respectively (Kazaryan & Kazaryan 1980; Kazarian *et al.* 2010). Direct observations of these galaxies at the primary focus of 2.6-m telescope of the Byurakan Astrophysical Observatory (BAO, Armenia) have shown that they are all spirals (Egiazaryan 1983). Spectral observations of galaxies NGC 7769, 7770 and 7771, conducted with 6-m BTA telescope of the Special

Astrophysical Observatory (Russia), have shown that forbidden lines of sulfur and oxygen, and Balmer emission lines of hydrogen are present in their spectra (Kazaryan & Kazaryan 1989). It was found that galaxies NGC 7769, 7770 and 7771 together are a physical triplet of galaxies located at a distance of 60 ± 4 Mpc. Later, these galaxies have been studied as an isolated quartet including also the small galaxy NGC 7771A (Nordgren *et al.* 1997). This system was also observed in 21-cm HI line (Nordgren *et al.* 1997; Noordermeer *et al.* 2005).

In the current work, we report results of the optical interferometry of the system and analyze the kinematics of galaxies. A detailed description of the morphological features of the galaxies is presented. We also discuss the influence of interaction on the kinematics, dynamics and star formation in the system. Known models of galaxy interactions are based mostly on statistical observational data. We try to illustrate how and to what extent these models can be applied to explain the features of the galaxies in this system.

2. Description of the system

Using *gri* color images of the Sloan Digital Sky Survey (SDSS; Ahn *et al.* 2014), we morphologically classified the galaxies of the system, measured their geometric and photometric parameters, as well as analyzed color profiles of NGC 7769. Table 1 presents parameters of the galaxies. Figure 1 shows SDSS *g, r, i* image of the system. Below we pay attention to some remarkable properties of the galaxies of the system and analyze them in order to illustrate some interesting features of processes caused by close interaction of the galaxies.

The structure of spiral arms of NGC 7769 can be classified as having an arm-class 7 (grand-design) according to the scheme in Elmegreen & Elmegreen (1987): two symmetric long outer arms and flocculent inner arms. Spiral arms of NGC 7771 have arm-class 12 (grand-design) according to the scheme in Elmegreen & Elmegreen (1987): two symmetric long arms dominating in the disk. Radio observations in Nordgren *et al.* (1997) and Noordermeer *et al.* (2005) showed that the southern arm

Table 1. Parameters of galaxies in the quartet.

NGC	7769	7770	7771	7771A
Kaz	346	347	348	–
RA (deg)	357.76659	357.84442	357.85435	357.80505
Dec (deg)	20.15045	20.09680	20.11160	20.103411
V_T (km s ⁻¹)	4220	4045	4260	4060
Morph.	Sb	SABc	SBb	Sm
Arm class	7	4	12	–
<i>g</i> -band D_{25} (arcsec)	196	65	250	50
PA	30°	60°	70°	114°
incl.	40°	45°	65°	70°
<i>g</i> mag	12.61 ± 0.04	14.16 ± 0.02	12.47 ± 0.01	16.70 ± 0.07
<i>u</i> – <i>g</i>	1.35 ± 0.11	1.20 ± 0.05	1.51 ± 0.03	1.14 ± 0.17
<i>g</i> – <i>r</i>	0.75 ± 0.07	0.69 ± 0.04	0.86 ± 0.02	0.50 ± 0.12
<i>g</i> – <i>i</i>	1.14 ± 0.07	1.01 ± 0.03	1.32 ± 0.01	0.70 ± 0.12
<i>g</i> – <i>z</i>	1.63 ± 0.06	1.33 ± 0.03	1.73 ± 0.01	1.14 ± 0.01
log (<i>m</i> / M_\odot)	10.27 ± 0.15	9.56 ± 0.11	10.49 ± 0.09	8.26 ± 0.20

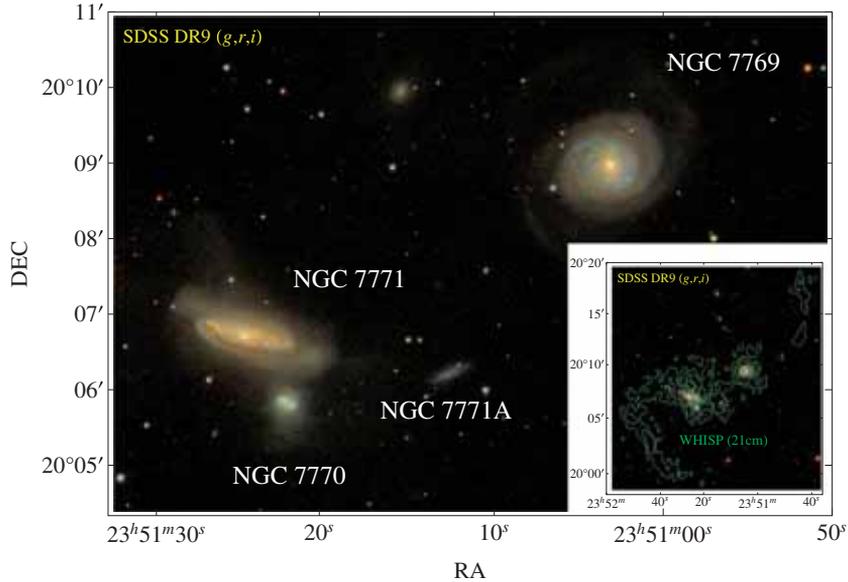


Figure 1. The SDSS *g, r, i* image of the system. Inset: a broader region containing the system, where tidal arms extend much further in the HI radio waveband. Intensity contours of the WHISP 21-cm radio map (Noordermeer *et al.* 2005) are overlapped on the SDSS image.

of NGC 7771 extends much further than what is visible in the optical image, making a bridge to NGC 7771A to the West and ending with a region of bright radio emission, see Figure 1. The northern arm extends up to about 10–15 optical radii of the galaxy (16 arcmin) and becomes an arc stretched around NGC 7770 to the South. The long bar (21 kpc) of NGC 7771 also stands out. The spiral arms of NGC 7771, as well as outer arms of NGC 7769 have tidal origin (e.g. Toomre & Toomre 1972; Kormendy & Norman 1979; Kendall *et al.* 2011). The existence of bar is a characteristic feature of most grand-design galaxies (e.g. Elmegreen & Elmegreen 1989). Probably, the bar of NGC 7771 also has a tidal origin (see, Noguchi 1987). The system of NGC 7771, 7770 and 7771A is embedded in a common envelope of neutral hydrogen (Noordermeer *et al.* 2005). Although NGC 7771A has not been included in the list of Kazarian galaxies (obviously, because of low surface brightness), however, it is the bluest object in the quartet (see colors in Table 1), which evidently suggests that it also has a UV excess caused by a high rate of star formation.

On the SDSS optical images toward the North and South from NGC 7771, there are some visible faint regions of diffuse emission probably associated with stars and hot gas driven out by the minor interaction with NGC 7770 (Alonso-Herrero *et al.* 2012). A comparison of the SDSS images of different colors shows that NGC 7770 has a weak but long enough bar (from NE to SW). Spiral arms of NGC 7770 have arm-class 4 according to scheme in Elmegreen & Elmegreen (1987): one remarkable distorted arm, and the second arm is much shorter. Because of the low resolution of images, however, in earlier works of Egiazaryan (1983) and Nordgren *et al.* (1997), it was concluded that NGC 7770 has two nuclei. However photometric analysis of the SDSS images of five colors shows that NGC 7770 has seven bright HII regions

with intensive star formation, some of which have brightness comparable with the brightness of the nucleus of the galaxy. Both intensive star formation and significant disturbances of arms are caused by the interaction with more massive (about 8 times) neighbor NGC 7771 (e.g. Di Matteo *et al.* 2007). In Alonso-Herrero *et al.* (2012), it was concluded that NGC 7770 has already experienced first passage around NGC 7771.

Supernova (SN) 2003hg was discovered in NGC 7771 galaxy at the coordinates RA (deg) = 357.85054, Dec (deg) = 20.11064, and was classified as Type II SN (collapse of a massive stellar core), discovered immediately after the explosion (Elias-Rosa *et al.* 2003). Reddening in the spectrum of the SN caused by dust in the host galaxy is significant. However, direct inspection of the explosion site on the SDSS *u*- and *g*-band images allows us to see an overlap of the SN with a giant region of intensive star formation located at the West side of galaxy bar. Such a location of SN is in good agreement with the known correlations of core-collapse (Types Ibc and II) SNe with star formation in galaxies (e.g. James & Anderson 2006; Hakobyan *et al.* 2008), including also star formation induced by an interaction with neighbor galaxies (e.g. Nazaryan *et al.* 2013; Hakobyan *et al.* 2014).

3. Observations

In order to study the velocity fields of the galaxies, the observations were carried out at the 2.6-m telescope of BAO on 8 November 1996, with the ByuFOSC (Byurakan Faint Object Spectral Camera) in the interferometric mode, attached at the prime focus of the telescope. This device, as well as the pointing-guiding system ‘Bonneter’, were designed and assembled at the Marseille Observatory in 1996. ByuFOSC includes a focal reducer (bringing the original F/4 focal ratio of the prime focus to F/2) with parallel beam allowing the installation of the various dispersing elements, filter wheel, and a CCD detector (Thomson 1028 × 1060 matrix with 5e⁻ rms read-out noise and 19 μm pixel size). The scanning Fabry–Perot interferometer was placed in the parallel beam. The detector was used in the half-obscured mode, allowing a quick shift of an exposed image to the obscured part of the matrix and the continuation of exposure of the next channel while reading out.

ByuFOSC is very similar to CIGALE (Boulesteix *et al.* 1984). The instrument provides a useful field of 6.5′ × 13′ with one pixel equivalent to 0.77″ on the sky. The field was scanned through 24 steps, the exposure time was 420 s per channel, providing a total exposure time of 2 h 48 m. The quality of seeing was about 2″. The H α line was isolated with a narrow-band interference filter centered at 6568.6 Å with a FWHM of 10.3 Å. General data reduction, night sky lines and stellar continuum subtraction and velocity field measurements are done similar to Laval *et al.* (1987).

4. Velocity fields and rotation curves

Based on the H α velocity fields (Figure 2), we calculated the rotation curves of the galaxies (Figure 3) by using data points within sectors along the maximal gradient direction, see isovelocity contours in Figure 2.

Maximal rotational velocity of NGC 7769 is observed at the radius of around 15 arcsec from the galaxy nucleus. The rotational velocities in Figure 3 are in good

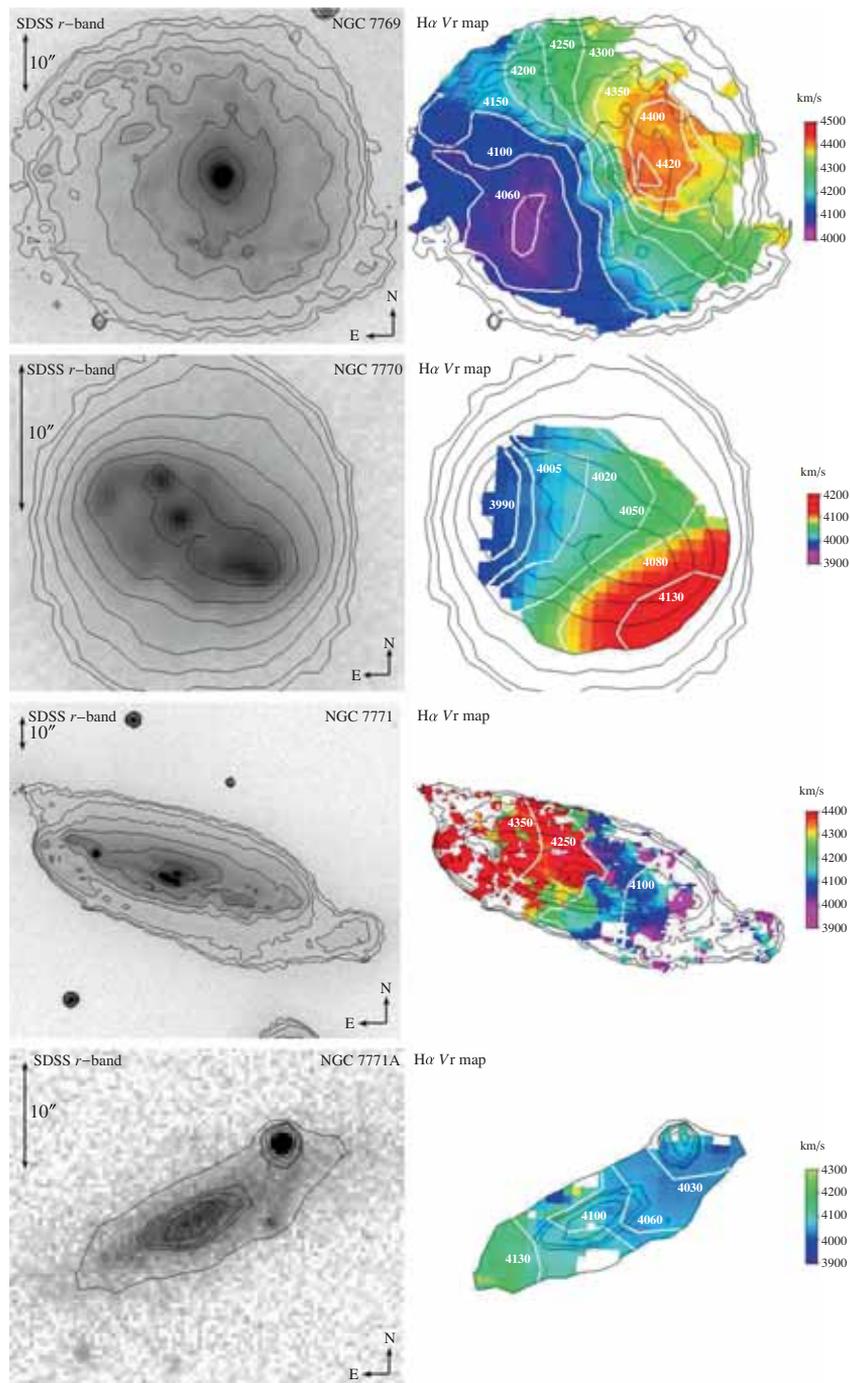


Figure 2. $H\alpha$ velocity fields of galaxies NGC 7769, 7770, 7771 and 7771A, overlapped by the SDSS r -band isophotes (black), and isovelocity contours (white). The outer isophote corresponds to $22 \text{ mag arcsec}^{-2}$ for NGC 7769, 7770 and 7771, and to $23 \text{ mag arcsec}^{-2}$ for NGC 7771A.

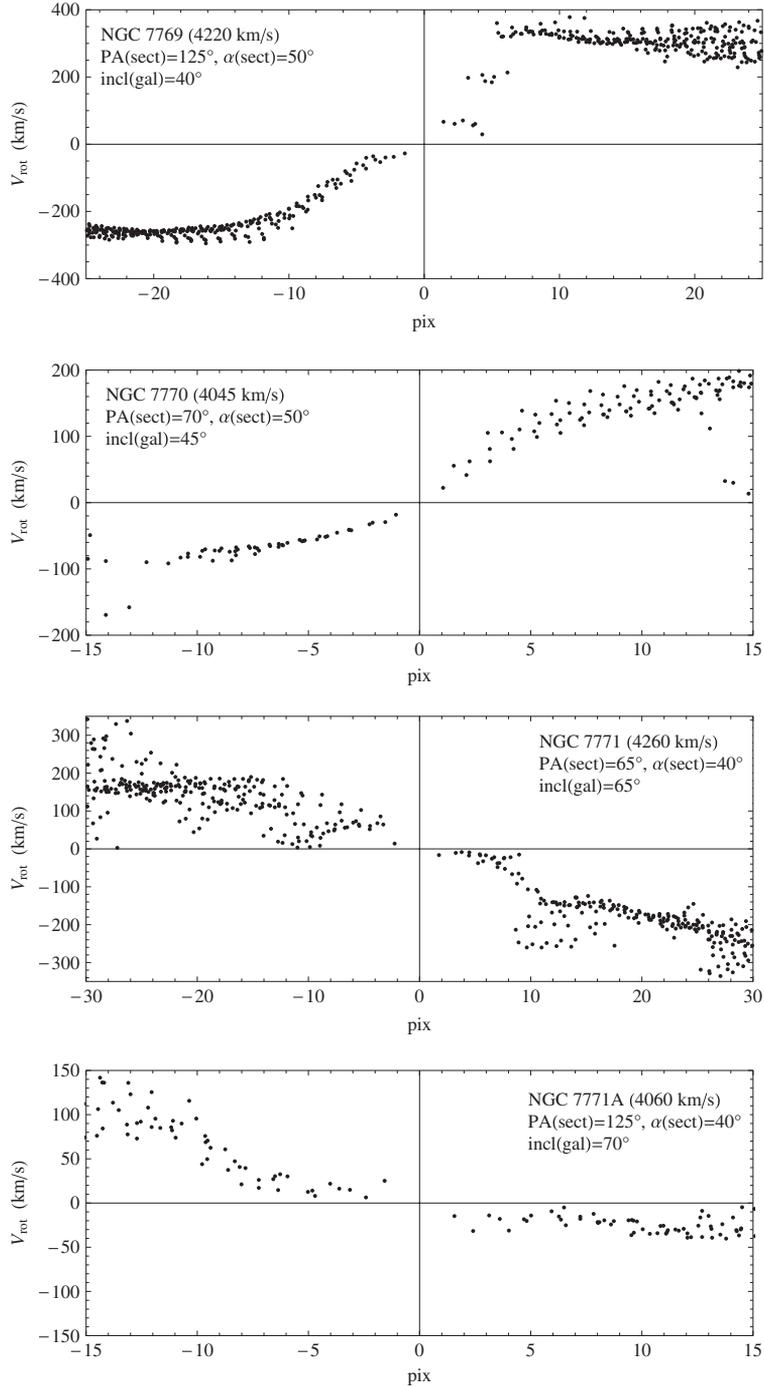


Figure 3. Derived rotational curves of the galaxies. One pixel on the horizontal axis corresponds to 0.77 arcsec. For each plot, the radial velocity of the galaxy center, the angle and PA of the sector used to obtain velocity data, as well as the inclination of galaxy used in the calculations are shown.

agreement with the HI measurements (316 km s^{-1}) in Chengalur *et al.* (1993). Our measurements of velocities, having a better spatial resolution compared with those of the previous studies (Chengalur *et al.* 1993; Nordgren *et al.* 1997), reveal weak perturbations of the rotation curve of NGC 7769, which may be caused by interaction with NGC 7771.

The same cannot be said about the velocity field of NGC 7771. Figures 2 and 3 show that there are perturbations and large dispersion in radial velocities at distances larger than 10–15 arcsec from the nuclei. This distance is about half radius of the bar. Evidently, this scatter of radial velocities can be explained by the fact that part of the arms are included in the sector used to calculate radial velocities (sector angle is 40°). However the asymmetric profile along the major axis suggests that Northern and Southern arms do not have the same radial velocity profiles. The asymmetric tidal forces of NGC 7769 and NGC 7770 affecting on NGC 7771, seem to be a natural cause of that.

The rotation curve of NGC 7770 is significantly skewed. This is probably because of the strong harassing interaction with the more massive NGC 7771, see Alonso-Herrero *et al.* (2012). The rotation curve of NGC 7771A is typical for a late type Sm galaxy.

By analyzing velocity fields, sizes, and shapes of spiral arms of NGC 7771 and NGC 7769, in Nordgren *et al.* (1997), it has been suggested that NGC 7771 and NGC 7769, which have a 2 : 1 mass ratio, appear to be having a prograde–retrograde interaction, with NGC 7769 being the retrograde one. Our data support this conclusion. This conclusion is in agreement with the latest models of galaxy collisions (Di Matteo *et al.* 2007) showing that during direct collisions, tidally induced spiral arms are much longer and brighter than those during retrograde collisions. We can conclude that galaxies NGC 7769 and NGC 7771 already have passed the first pericenter stage, however, probably the second encounter has not yet happened. The first pericenter distance should have been large enough (around few sizes of the galaxies), so that large disturbances in rotation curves have not yet appeared.

5. Photometry and color analysis of NGC 7769

Studies of color profiles of galaxies allow to find out interesting features of their evolution, interaction, and star formation (e.g. Bakos *et al.* 2008; Tortora *et al.* 2010). NGC 7769 has small inclination, therefore it is possible to adequately study its radial color profiles, which are quite noteworthy. In Figure 4, SDSS *g* and *r* surface brightness profiles are plotted. Brightnesses are measured in concentric ellipses having position angle (PA) of the ellipse with the *g*-band brightness of $25 \text{ mag arcsec}^{-2}$. The characteristic break at the distance $R_b = 0.6 R_{25}$ from the nucleus with a smaller gradient after that distance is clearly visible. However, we should note that the profile of stellar mass surface density, which is constructed according to the method in Bell *et al.* (2003) using the colors and Kroupa initial mass function (IMF), is without a break. Mass density and *r*-band surface brightness profiles are the same until the break radius, however, after that distance they are different. A Kolmogorov–Smirnov test rejects that the brightness profiles of both *r*- and *g*-bands and mass profile could be from the same parent distribution.

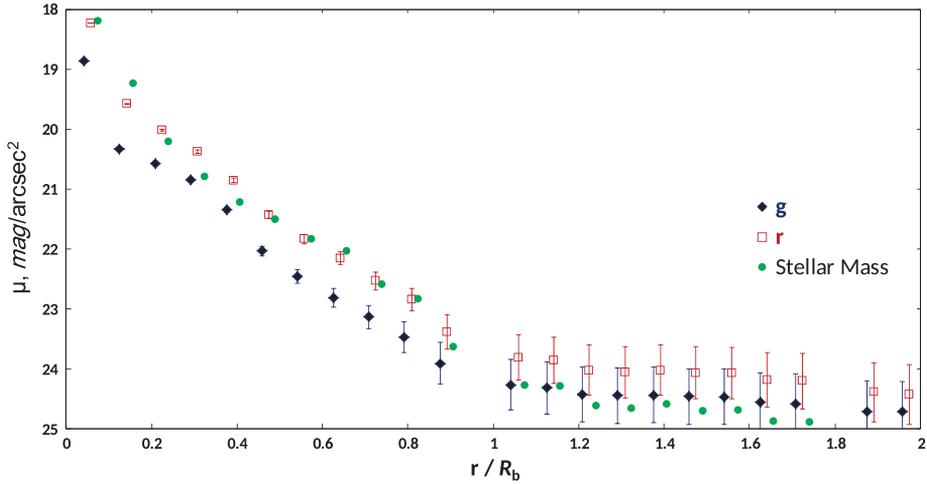


Figure 4. SDSS *g* and *r* surface brightness profiles and stellar mass surface density of NGC 7769. The distance in the horizontal axis is normalized to the break radius $R_b = 0.6 R_{25}$. Stellar mass surface densities are in arbitrary units with the same scaling ($-2.5 \log[m]$). Mass density and *r*-band surface brightness profiles are the same until the break radius, however, after that distance they are different.

In Figure 5, mean color indices within the above mentioned elliptical annuli are shown. At the distance of about $0.3 R_b$ (3 kpc) there is a concentric region with minimum color indices ($g - r = 0.62 \pm 0.02$), which has a higher fraction of young stars. All the mentioned observational results allow us to classify NGC 7769 as a galaxy with Type III profile of surface brightness, according to classification in Erwin *et al.* (2005), see also Bakos *et al.* (2008). Different authors suggested several possible versions of the origin of the characteristic profile, all of them implying an external

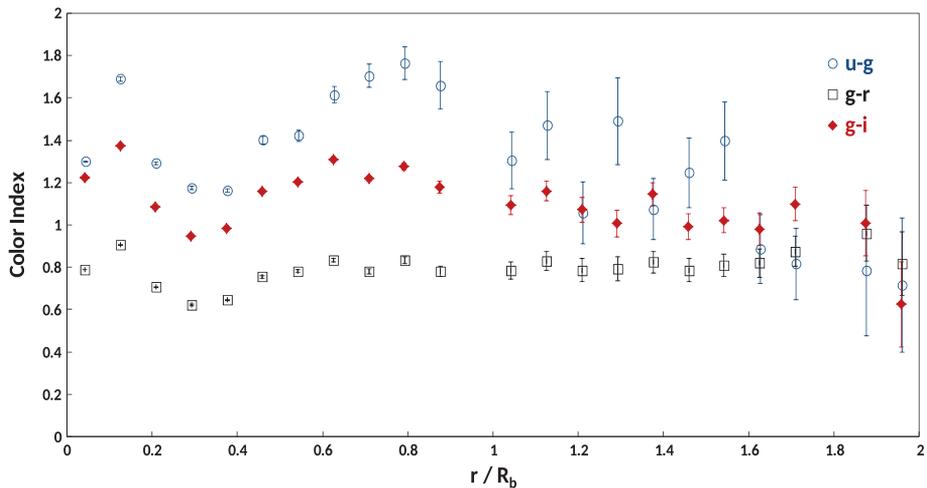


Figure 5. Radial profiles of color indices of NGC 7769.

influence on a galaxy. In case of NGC 7769, we prefer the scenario of Younger *et al.* (2008) explaining Type III profiles by a flyby of a neighbor galaxy with a high-eccentricity orbit. In our case, it is NGC 7771 galaxy, which has already passed the phase of first pericenter of encounter with NGC 7769.

6. Summary

The quartet of galaxies NGC 7769, 7770, 7771 and 7771A is a system of interacting galaxies. In this paper, we present a Fabry–Perot imaging study of the system in H α line, as well as an analysis of the color profiles of NGC 7769. We came to the following main conclusions:

1. Close interaction between the component galaxies of the system has produced morphological features that are characteristic of the interactions. We have detected features such as tidal arms, spiral arms induced by close interaction, bars and induced star formation.
2. From the results of our interferometric observations, we obtained the radial velocity profiles of galaxies. The rotation curve of NGC 7769 is weakly distorted. The rotation curve of NGC 7771 is strongly distorted by the tidal arms caused by direct flyby of NGC 7769 and flyby of a smaller neighbor NGC 7770. The rotation curve of NGC 7770 is significantly skewed because of the interaction with the much massive NGC 7771.
3. The radial velocity profiles and morphological disturbances suggest that the NGC 7769 and NGC 7771 have passed the first pericenter stage, however, probably the second encounter has not yet happened.
4. The surface brightness profile of NGC 7769 has a characteristic break, and profiles of color indices have a minimum at a concentric region of intensive star formation induced by the interaction with NGC 7771.

Study of such systems with methods combining photometric and visual analysis is an effective way to clarify features of star formation in different stages of interaction. Ongoing and future surveys using integral field spectroscopy will also allow to explore the spatial distribution of star formation in interacting systems.

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