A New Photometric Look at M51

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Abstract. A new technique is used to derive the extinction and age of populations in the interacting galaxies NGC5194 & NGC5195 from high S/N multicolor photometric data. A new evolutionary scenario of the interaction is proposed.

Keywords: M51, NGC5194, NGC5195, galaxies, photometry

1. Introduction

Detailed investigation of populations in Local Group (LG) galaxies using stellar photometry has recently become very popular (Aparicio 1998). This is a direct way to study the populations and evolution of galaxies. However, even for LG objects it is difficult to reach the required photometry depth. To reconstruct the star formation history of more distant galaxies different techniques should be applied. Historically, the most popular method is an evolutionary population synthesis (Tinsley 1980; Arimoto & Yoshii 1986), which treats the entire galaxy as a single zone unit. Such an approach is probably satisfactorily applicable only for ellipticals. However, it seems too simplified in the case of spiral disks. To improve the tools available for the evolutionary analysis of galaxies, a new method for multicolor mapping is introduced and applied for the interacting galaxy pair NGC5194/95 (hereafter, M51 system).

M51 is a well studied nearby system of two overlapping galaxies seen nearly face-on, and therefore suitable for testing new methods and 2-D mapping techniques. Since the interpretation of the results of optical photometry always suffer from the influence of dust residing in galaxies, it is important to know the extinction properties of the galaxies under consideration. For this purpose, overlapping galaxies are particularly suitable, allowing precise derivation of an attenuation law and the amount of the extinction in the foreground galaxy (White & Keel 1992). Moreover, results of an extensive dynamical modeling of M51 are available (Barnes 1998), and hence can be used for a comparison of the photometrically derived parameters with the ones determined by other independent methods.
Figure 1. CMDs of the galaxies NGC5194 & NGC5195. Galaxies are simply separated by declination. Reddening arrow is given according to the M51 attenuation law.

2. Observations and Reductions

Observations were carried out at Kiso Observatory (Japan) using the 1.05 m Schmidt telescope on February 17 & 18 and March 7, 1994. The CCD camera Tek 1024 (read-out noise 14 $e^-$, scale 0.75 $''$/pixel, and field of view 12.5' $\times$ 12.5') was used. The open cluster M67 was observed every night as a standard field. More than 150 exposures of M51 of 30 – 1800 seconds duration and image quality of 3$''$ – 5$''$ were taken in total. The standard $BVRCI_C$ and narrow-band $H\alpha$ ($\lambda_0 = 658$ nm; $\delta\lambda = 2.5$ nm) filters, together with $Z$ ($\lambda_0 = 518$ nm; $\delta\lambda = 21$ nm) filter of Vilnius system.

Standard reductions were made with IRAF. The $2-D$ aperture photometry (scanning the entire field with a constant step of $\sim 4''$ and aperture of $\sim 8''$) was performed using an AFO package (Bridžius & Vansevičius 1998).

Assuming the distance to the M51 system to be equal to 8.4 Mpc (Feldmeier, Ciardullo, & Jacoby 1997), each circular $\sim 8''$ aperture corresponds to the region of $\sim 330$ pc in galaxies (hereafter, zone). In the color-magnitude diagram (CMD) (Fig. 1) zones of both galaxies are shown separately. For further discussion we use only precisely measured ($\sigma < 0.\,''03$) zones with $V < 23.\,m5$.

It is worth noting the different morphologies and fine structures of both CMDs (Fig. 1). Most of the "streaming features" are parallel to the reddening arrow, and can be attributed to the dust influence.

3. Extinction in M51

The problem of dustiness of galaxies at different evolutionary stages is widely discussed recently. In particular, the dilemma of whether the spiral disks are optically thick or thin is debated (Davies & Burstein 1995). To clarify the problem of spiral disk dustiness, we determine the amount of extinction and the attenuation curve in NGC5194 using NGC5195 as a tracer. The facts supporting the validity of such a method are: a) NGC5195 is behind NGC5194; b) NGC5195 is a source bright enough to have a high $S/N$ ratio even in the most obscured parts of the galaxy; c) NGC5195 is found to be a regular S0 galaxy in the near-infrared (Thronson, Rubin, & Ksir 1991), therefore it is possible to compare symmetrically located zones.
Figure 2. $V$ (panel (a): solid line - clear (without dust signatures) region, dashed line - dusty region) & $B-V$ (panel (b): no shading - clear region, shaded histogram - dusty region) distributions of zones used to derive the attenuation law and extinction in the disk of NGC5194.

Table I. Properties of the extinction in NGC5194.

| Parameter      | NGC5194       | Milky Way |
|----------------|---------------|-----------|
| $R_V$          | 2.56 ± 0.13   | 3.10      |
| $E_{V-R}/E_{B-V}$ | 0.67 ± 0.06  | 0.56      |
| $E_{V-I}/E_{B-V}$ | 1.33 ± 0.08  | 1.25      |
| $E_{B-I}/E_{B-V}$ | 2.41 ± 0.13  | 2.25      |
| $E_{R-I}/E_{B-V}$ | 0.66 ± 0.09  | 0.69      |
| $E_{Z-V}/E_{B-V}$ | 0.30 ± 0.05  | 0.28      |

We measured two regions (symmetric with respect to the NGC5195 center and bar), each consisting of 50 zones ($\sim 20^{\prime\prime} \times 40^{\prime\prime}$) at an average distance of $\sim 40^{\prime}$ from the center. Visual inspection of the $B$ image helped to locate the region relatively free of dust signatures, and then the corresponding dusty region was chosen on the opposite side of the center and bar. The $V$ and $B-V$ histograms of the investigated zones are shown in Figure 2. The parameters of the derived attenuation curve are given in Table I (definition of the extinction: $A_V = R_V \cdot E_{B-V}$, is used). The derived median value of the extinction for the interarm region at $\sim 11$ kpc distance from the center of NGC5194 is $A_V = 0.7 \pm 0.3$.

Numerous determinations of the amount of extinction in NGC5194 have recently been obtained. Smith et al. (1990) derived $A_B = 0.9$ using NGC5195 as a tracing source. Rix & Rieke (1993) put a limit on the global optical depth of NGC5194 disk of $\tau_V < 1 - 2$. Nakai & Kuno (1995) determined $A_V = 1.16 - 4.38$, based on a study of 37 HII regions in the disk of NGC5194. Beckman et al. (1996) concluded that optical depth in the $V$ band, averaged out to a radius of three scale lengths from the center of NGC5194, is 0.7. These results mainly ascribe properties of the arm regions, however they do not contradict our conclusion that the disk of NGC5194 is opaque in the interarm regions even at a large distance from the center.

However, such a conclusion is in contradiction with the one drawn by White, Keel, & Conselice (1996) from a study of nine overlapping galaxy systems. They derived the extinction $A_B = 0.3 - 2.3$ in the arm and $A_B = 0.08 - 0.47$ in the interarm regions. NGC3314 is the only...
system in their sample which possesses significant extinction in the arm ($A_B = 1.11 - 1.64$) and in the interarm ($A_B = 0.77 - 1.75$) regions, which supports our conclusion that some of the spiral disks are opaque even in the interarm regions.

The color excess ratios derived for the outer part of the disk are very close to those of the Milky Way (MW) extinction law. Taking into account the same conclusion reported by Panagia et al. (1996) for the central part of NGC5194, we assume that color excess ratios are constant throughout the disk of this galaxy.

### 4. Abundance and effective age of zones

To avoid the age-abundance degeneracy in determining the effective age of zones, global distribution of the abundance should be derived. Abundance analysis of HII regions (Díaz et al. 1991; Zaritsky, Kenney, & Huchra 1994) indicates the mean abundance to be above solar: $12 + \log(O/H) \sim 9.3$, with a gradient equal to $\sim -0.06$ dex/kpc. Alternatively, Hill et al. (1997) explained the observed UV color gradient in terms of radial extinction gradient, rather than of abundance.

We define an abundance parameter (independent of the extinction) as follows: $Q_{ZV_{BV}} = (Z-V) - (B-V) \cdot E_{Z-V}/E_{B-V}$. $Q_{ZV_{BV}}$ is a measure of Mg (518 nm) spectral feature strength, which is a good abundance indicator (Barbuy 1994; Casuso et al. 1996). Plotting $Q_{ZV_{BV}}$ vs. radial distances from the galaxy centers, we do not see the abundance gradient except for the very central region inside the radius of $\sim 1.5$ kpc. However, a significant difference of abundances between NGC5194 and NGC5195 is found. Therefore, deriving the ages of zones we assume no abundance gradient across the disk of both galaxies. The abundances $Z=0.05$ for NGC5194 and $Z=0.02$ for NGC5195 are adopted, respectively. Such an assumption does not significantly affect differential analysis of the age distribution of populations in the disk outside the inner Lindblad resonance (radius $\sim 1.25$ kpc) of NGC5194 (Elmegreen, Elmegreen, & Seiden 1989), and outside the comparable radius in NGC5195.

Let us introduce a parameter $Q_{BV_{I}} = (B-V) - (V-I) \cdot E_{B-V}/E_{V-I}$ as a measure of the effective age of each zone, which is again extinction-independent. Actually, both $Q$ formulae are only correct in the case of a star residing behind the dust cloud (screen). The validity of dusty screen approximation in the case of face-on galaxies was shown by González & Graham (1996). Diagram V vs. $Q_{BV_{I}}$ constructed from our data sample, in contrast to Figure 1, shows no prominent "streaming features", which can be attributed to the influence of extinction. All this
indicates that $Q_{BV1}$ is a reddening-free parameter in the case of face-on galaxies. Figure 3a shows calibration of $Q_{BV1}$ vs. age for single (age) stellar populations (SSPs) calculated from the model spectra library GISSEL96 (Bruzual & Charlot 1993). Figure 3b provides histograms of the parameter $Q_{BV1}$ for both galaxies of the M51 system, which are simply separated by declination. A significant difference in age between the two galaxies is obvious even if the interfering influence of the Northern arm of NGC5194 projected onto NGC5195 is neglected. The derived ages of the bulk of population in NGC5194 & NGC5195 are $390 \pm 70$ Myr and $710 \pm 120$ Myr, respectively. The gray-coded population age distribution in galaxies is shown in Figure 4.

Recent dynamic modeling suggests two starbursts in M51, the first less than $\sim 100$ Myr ago and the second one $\sim 400$ Myr ago (see Barnes (1998) for discussion). We derive the age for a bulk of zones in NGC5194 to be $\sim 390$ Myr, in good agreement with the dynamical prediction. Zones in NGC5195 are $\sim 320$ Myr older. If one assumes this age difference to be a characteristic time between two close-up passages, the predicted age $\sim 70$ Myr for the last passage again is in good agreement with the dynamical modeling. Therefore, our study indicates that the evolutionary scenario of M51 has had at least three periods of activity. The first starburst occurred $\sim 700$ Myr ago in NGC5195 during a close-up passage with NGC5194, when, probably, NGC5195 was transformed to an S0 galaxy. The next starburst took place after $\sim 300$ Myr, when the bulk of the population in NGC5194 was formed, and finally the last one occurred again after $\sim 300$ Myr when the present grand-design appearance of NGC5194 was "touched up".

5. Conclusions

Main conclusions are the following: a) the attenuation law determined in NGC5194 is close to MW standard extinction law; b) the opaque interarm region at distance $\sim 11$ kpc from the center of NGC5194 supports optically thick models of spiral disks; c) the derived effective age $\sim 400$ Myr for the bulk of NGC5194 zones agrees well with the predictions of recent dynamic modeling of M51; d) the effective age
∼ 700 Myr derived for the bulk of zones in NGC5195 implies a scenario with three periods of starburst activity. However, more sophisticated radiative transfer models and realistic star-dust distributions as well as 2 – D models of the evolution of spiral disks, instead of simple SSP approach, are crucial for the interpretation of the mapping data.

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NGC 5195

NGC 5194

\( V \) [mag arcsec\(^{-2}\)]

\( B - I \)

\( A_v = 1.0 \)
a) \( V \) [mag arcsec\(^{-2}\)]

b) \( B - V \)
