YOUNG POPULATIONS IN THE NUCLEI OF BARRED GALAXIES

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Abstract. We have conducted a $UBVRI$ and $H_\alpha$ CCD photometry of 5 barred galaxies, NGC2523, NGC2950, NGC3412, NGC3945 and NGC5383, along with SPH simulations, in order to understand the origin of young stellar populations in the nuclei of barred galaxies. The $H_\alpha$ emissions which are thought to be emitted by young stellar populations are either absent or strongly concentrated on the nuclei of early type galaxies (NGC2950, NGC3412, NGC3945), while they are observed in the nuclei and circumnuclear regions of intermediate type galaxies with strong bars (NGC2523, NGC5383). SPH simulations of realistic mass models for these galaxies show that some disk material can be driven into the nuclear regions by strong bar potentials. This implies that the young stellar populations in the circumnuclear regions of barred galaxies can be formed out of such gas. The existence of the nuclear dust lanes is an indication of an on-going gas inflow and extremely young stellar populations in these galaxies, because the nuclear dust lanes such as those in NGC5383 are not long-lasting features according to our simulations.

Keywords: galaxies, photometry, population, SPH simulations

1. INTRODUCTION

Barred galaxies are characterized by the prominent bars across the nuclei of disk galaxies. Although bulges of disk galaxies are thought to consist of old stellar populations formed in the early phase of galaxy evolution, there are some disk galaxies, especially early type barred galaxies, which have young stellar populations in their nuclei (Benedict et al. 1992). The association of bars with nuclear young stellar populations which are delineated as ”hot spots” was recognized first by Sersic & Pastoriza (1965, 1967). Most of the galaxies with young stars in their nuclei show twisted isophotes, indicating triaxial structures (Stark 1977; Wozniak et al. 1995). Hence Wozniak et al. (1995) classified the nuclear morphology of galaxies according to the characteristics of isophotal twists.

Recent hydrodynamical simulations have shown that strong bars are very effective in transporting the disk material into the inner regions of galaxies, and so the young stellar populations can form from the gas infalled into the nuclear region (Friedli & Benz 1993; Ann & Kwon 1996). Thus a detailed analysis of star formation rates and the distribution of the young stellar populations in observed galaxies may
provide observational constraints for the gas inflow model driven by a bar potential. The purpose of the present photometry is to draw some insights into the physical conditions that allow young stellar populations in the nuclei of galaxies. Toward this end, we have conducted $UBVRI$ and $H\alpha$ photometry of five bright barred galaxies, and then derived realistic mass models from the observed surface brightness. We have also carried out an extensive suite of hydrodynamic simulations of barred disk galaxies by adopting the derived mass models.

2. OBSERVATIONS AND REDUCTION

The observations of the program galaxies were made on the two photometric nights during the observing run in March 1997 with a Tex 1024 CCD ($1024 \times 1024$, 24$^2$ $\mu$m$^2$ pixels) attached at the Cassegrain focus of the 1.8 m Doyak Telescope of Bohyunsan Optical Astronomy Observatory (BOAO) in Korea. The gain and readout noise of the CCD were $3.5e^{-1}$/ADU and $6.4e^{-1}$, respectively. The images were recorded with $2 \times 2$ on-chip binning which gives the image scale of 0.′′68/pixel. The images were obtained with Johnson-Cousin $UBVRI$ and $H\alpha$ filters. Flat field exposures were made on the twilight sky. Several standard stars of Landolt (1992) and Massey et al. (1988) were observed during the nights for the absolute calibration of the sky brightness and $H\alpha$ flux. The seeing was about 2′′ throughout the nights.

The basic reductions were carried out using the CCDRED package within IRAF. The flat fielded frames of galaxy images were subtracted and divided by sky frames which were obtained by fitting the sky regions surrounding the galaxy images. We applied a variable width Gaussian smoothing to increase the signal-to-noise ratios of the observed data in the outer part of the galaxy. The $H\alpha$ flux calibrations were made by subtracting the scaled $R$-band images from the $H\alpha$ images. The scale factors were determined by the stars and the regions devoid of emissions in the galaxy.
3. NUCLEAR MORPHOLOGY AND YOUNG POPULATIONS

The presence of young stellar populations in the nuclear region of observed galaxies can be inferred from the nuclear structures such as nuclear ring, nuclear spiral arms and nuclear dust lanes. Usually these structures are associated with HII regions of newly formed massive stars. These nuclear structures distort the shape of the isophotes in the nuclear region and make the appearance of the bulges triaxial (Shaw et al. 1995; Wozniac et al. 1995).

Fig. 1 displays the $V$-band isophotal maps of the five barred galaxies. We can see pronounced isophotal twists in the nuclear regions, which suggest the bulges of the three SB0 galaxies (NGC 2950, NGC 3412 and NGC 3945) are triaxial. But the fact that there is no nuclear structure such as those mentioned above implies no young stellar population in their bulges. However, NGC 5383 shows very complicated structures which resemble nuclear spiral arms and nuclear ring. Detailed analysis of the nuclear morphology of NGC 5383 (Ann and Kim 1998) showed that the spiral patterns are made by the sharply curved nuclear dust lanes obscuring the nuclear ring. Since dust lanes are located in the high density regions where stars can form, we expect young stellar populations in the nuclear region of NGC 5383.

The strong H$_\alpha$ emission can provide a more direct evidence for the presence of the young stellar population. As shown in Fig. 2, there are strong H$_\alpha$ emissions in the nuclear regions of two intermediate type galaxies NGC 2523 and NGC 5383. Most of the H$_\alpha$ emissions in these galaxies come from the circumnuclear regions which are similar to the nuclear rings such as those in NGC 4314 (Benedict et al. 1992; Ann & Kwon 1996) and NGC 3351 and NGC 4303 (Colina et al. 1997). However, the shape of the nuclear ring of NGC 2523 is very different from that of NGC 5383 due to the different bulge morphologies of two galaxies. There are virtually no H$_\alpha$ emissions in the bulges of SB0 galaxies NGC 2950 and NGC 3412, while the H$_\alpha$ emissions are confined to the nucleus in NGC3945. It is evident from the surface brightness profiles in Fig. 2 that the distribution of the old stellar populations, which contribute most of the luminosities in the $UBVRI$ pass bands, is quite different from that of the young stellar populations inferred from the H$_\alpha$ profiles. The contribution of the young populations to the surface brightness profiles is almost negligible in the longer wavelengths.
Figure 2. Surface brightness profiles of five barred galaxies. There seem to be nuclear rings in NGC 2523 and NGC 5383 which show strong $H\alpha$ emissions. In NGC 3945 the strength of $H\alpha$ emissions is quite high but they are confined to the nucleus. There is virtually no $H\alpha$ emission in NGC 2950 and NGC 3412.

4. SPH SIMULATIONS

We have conducted SPH simulations to understand the origin of the young stellar populations in the nuclear region of the barred galaxies. The basic numerical methods employed in our SPH simulations are the same as those of Ann & Kwon (1996) and Lee et al. (1999). We assumed the model galaxies consisted of four components: bulge, disk, primary bar, and nuclear bar. We adopted the exponential disk of Freeman (1970) for the stellar disk component and the Plummer spherical potential for the bulge. Because our simulation was restricted to the two-dimensional disk, we used the bi-axial bar potential of Long & Murali (1992), which was uniform in space and constant in time. We assumed that the gaseous disk was isothermal at $T = 10^4$ K. The number of SPH particles was about 10000.

We have considered the following two models that can reproduce the observed morphologies of NGC 5383 (Model A) and NGC 2523 (Model B). The mass fractions in different mass components were derived from the decomposition of the observed surface brightness profiles into bulge, disk and bar.

Model A

$M_d : M_{bg} : M_{bar} = 3.6 : 3.4 : 2.7$, $a=0.5$, $a/b=4$, $\Omega = 2$,

$R_d = 0.4$, $b=0.1$, $M_{gas}=0.02$, $M_{sbar}=0.01$

Model B

$M_d : M_{bg} : M_{bar} = 4.0 : 2.8 : 3.0$, $a=0.4$, $a/b=4$, $\Omega = 2.5$,

$R_d = 0.3$, $b=0.09$, $M_{gas}=0.02$, $M_{sbar}=0.001$

where a is bar major axis length, $a/b$ is axial ratio, $R_d$ is disk scale length and $M_{sbar}$ is the mass fraction of the nuclear bar. In our simulations, the physical quantities are expressed as dimensionless variables with the following parameters:

$M_{tot} = 2 \times 10^{11}M_\odot$, $R_{sc} = 15$ kpc, $\tau_{sc} = \frac{1}{\sqrt{\bar{\rho}}} = 1.2 \times 10^8$ yrs,

$\Omega_{sc} = 16.4$ km/sec/kpc

Fig. 3 shows The distribution of the SPH particles and the mass fraction of the gas within 4.5 kpc from the center of the model galaxies.
Figure 3. The distribution of test particles and the mass fraction of infalled gas within inner regions (from top to bottom). Model A has a more massive bulge compared to Model B.

The bar pattern speeds are chosen to be low enough to ensure the ILRs for the model galaxies. One can see in the middle panel of Fig. 3 that the distributions of SPH particles resemble the nuclear morphology of NGC 5383 and NGC 2523. Moreover, the dust lanes in the bar of NGC 5383 are also seen in the gas distribution of Model A. This means that our models quite well represent the inner dynamics of the real galaxies. Both of our models lead to a significant gas infall toward the nuclear regions, which enables nuclear star formation there. The mass infall rate calculated from numerical simulations is order of \( \sim 0.5 \times \dot{M}_\odot \text{yr}^{-1} \) for both models with a strong primary bar (i.e. \( M_{\text{bar}}/M_{\text{tot}} \sim 0.3 \) and \( a/b=4 \)). This is consistent with the star formation rate inferred from the \( H_\alpha \) emissions of the observed galaxies.

5. SUMMARY AND DISCUSSION

Three SBO galaxies (NGC 2950, NGC 3412, NGC 3945) seem to have virtually no young stellar populations in the bulges except for the nuclei where some \( H_\alpha \) emissions are detected. The \( H_\alpha \) emissions from the nucleus of NGC 3945 is much stronger than those from the nuclei of NGC 2950 and NGC 3412 which have weaker bars than that of NGC 3945. Two intermediate-type barred galaxies, NGC 2523 and NGC 5383, with strong bars show strong \( H_\alpha \) emissions in the nuclear regions, indicating a significant number of young stellar populations there.

However, the elongated bulges of the three SBO galaxies are thought to result from the early secular evolution driven by the bars, that is, transport of disk material into the nuclear regions. The absence of the young stellar populations in their nuclear regions implies lack of the gas in the disks of these galaxies. There might have been some mechanisms which blew out the remnant gas from the galaxies after triaxial bulges were formed by the secular evolution driven by the bars.

Numerical hydrodynamic simulations of barred disk galaxies have shown that a bar potential can drive a spiral structure and non- axisymmetric flow motions along with shocks. The shocked gas loses its angular momentum and kinetic energy and spirals in toward the galactic center. Our SPH simulations based on realistic mass models show that strong bars with axial ratios larger than 3 are very effective in transporting the disk material into the nuclear regions of galaxies.
The nuclear rings can be made of young stars formed from the infalled gas with their morphology depending on the mass fractions in the bulge and the disk. The nuclear rings formed in galaxies with large bulge-to-disk ratio are aligned perpendicular to the primary bar while those with small bulge-to-disk ratio are aligned with the bar axis.

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