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BULGES OF TWO BARRED GALAXIES: NGC 3412 AND NGC 3941

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ABSTRACT

We have conducted near-infrared (J- and H-band) surface photometry for two early type barred galaxies, NGC 3412 and NGC 3941. The bulges of NGC 3412 and NGC 3941 show isophotal twists which indicate that they are triaxial. NGC 3412 has a very short bar and its bulge is more centrally concentrated than that of NGC 3941. The unusually short bar and the centrally concentrated triaxial bulge of NGC 3412 might be the result of bar dissolution. The colors of the nuclear region of NGC 3941 resemble those of the blue nuclei, implying the presence of young stellar populations.

Key Words : galaxies : photometry – galaxies : triaxial bulges – galaxies : individual(NGC 3412, NGC 3941)

I. INTRODUCTION

There have been many observational evidences that bulges may not be simply described by scale-down ellipticals. A large number of barred spirals are known to have triaxial bulges (Kormendy 1979; Ann 1995). The luminosity distribution of late type bulges are better fitted by exponential function than the $r^{1/4}$ law (Courteau, de Jong, & Broeils 1996). Recent *HST* WFPC2 images show that highly irregular bulges are not so unusual (Carollo et al. 1997).

The morphology of bulges has been analyzed by the shape of isophotes. Earlier studies of the isophotes of M31 lead to the conclusion that the bulge of M31 is triaxial because of the presence of isophotal twists (Lindblad 1956; Stark 1977). The isophotal twists can be caused by triaxial structures in galaxies (Bertola, Vietri, & Zeilinger 1991; Wozniak et al. 1995). Recent survey of the isophotal maps of barred galaxies (Ann 1995) showed that more than half of the 104 bright barred galaxies have triaxial bulges. Elmegreen et al. (1996) found that 64 % of 80 SB and SAB galaxies show isophotal twists from the survey of galaxies at near-infrared.

There are several mechanisms which can account for the isophotal twists observed in the inner regions of barred galaxies. Apart from the triaxial bulges mentioned above, the presence of two inner Lindblad resonances (ILRs), which affect orbits of stars and gas clouds (Shaw et al. 1993), and the secondary bars (Friedli & Martinet 1993) may distort the isophotes. Recent N-body simulations by Norman, Sellwood, & Hasan (1996) showed that the triaxial bulges are remnants of bar dissolution.

NGC 3412 and NGC 3941 are early type barred galaxies of which bulges are found to be triaxial due to the misalignments between the major axes of bulge and bar (Shaw et al. 1995). However, because of small misalignment between the major axes of bulge and disk, the bulge of NGC 3941 was classified as an oblate spheroid by Ann (1995). The colors of the nucleus of NGC 3412 are known to be bluer than those of the surrounding regions (Shaw et al. 1995). The purpose of the present study is to analyze the bulge morphology by near-infrared images and to draw some insights on the origin of the triaxial bulges. The basic parameters of NGC 3412 and NGC 3941 are given in Table 1.

In Section II, we present the observations and data reduction. The morphology and the luminosity distributions are described in Section III, and discussion and brief summary are given in the final section.

II. OBSERVATIONS AND DATA REDUCTION

We conducted a JH imaging of NGC 3412 and NGC 3941 with a PtSb 256 × 256 IR array attached to the modified Newtonian focus of the 1.8 m Plaskett Telescope of DAO in 1993 April. The pixel size is 30 μm which corresponds to $0.''67$ on the sky. The readout noise and the dark of the system were $62e^{-1}$ and $7e^{-1}s^{-1}$pixel^{-1}, respectively. The flat-field exposures were done on the twilight sky. The images were obtained with exposure times of 480 s in J- and H-band. Because dark noise is not insignificant, we obtained dark frames with various exposure times including those for the object frame. Several standard stars from Elias et al. (1982) were observed for the transformation of the instrumental magnitudes to the standard system. The seeing during the observation was about $3''$.

The basic reductions were carried out using the CCDRED package in IRAF. This procedure includes subtraction of a master bias frame with overscan correction, dark subtraction, trimming of the data section, and flat-fielding. Flat-fielding was made by dividing the bias subtracted images by a master flat field frame which was prepared by median combining of all the flat field frames in each filter.

The flat-fielded frames of galaxy images were sub-

Table 1. Basic data of NGC 3412 and NGC 3941

	NGC 3412	NGC 3941
R.A.(1950)	$10^h48^m14.^s50$	11°50′19.″67
Dec(1950)	$13^h40^m41.^s00$	37°15′52.″00
Morphological type	SBO	SBO
$\log D_{25}$	1.56	1.54
$\log R_{25}$	0.25	0.18
Total magnitude(B_T)	11.45	11.25
Galactic Extinction(B mag)	0.06	0.00
$(B-V)_T$	0.91	0.91
$(U-B)_T$	0.39	0.44
V_H	$865 \pm 27 km/s$	$928 \pm 5 km/s$

tracted and divided by sky frames which were obtained by fitting the sky regions surrounding the galaxy images, by using IRAF/SPIRAL. We applied a variable width Gaussian beam smoothing to increase the signal-to-noise ratio of the luminosity distribution in the outer parts of the galaxy. The absolute calibration of the galaxy photometry was made by the photometry of the standard stars. Because of the large photometric uncertainties, we derived only the zero points for each filter.

III. Results

(a) Isophotal Maps

Fig. 1 shows the isophotal maps of NGC 3412 (a, b) and NGC 3941 (c, d) with J-band in the left panel and H-band in the right. Here the tick intervals are 10 pixels (6.″7) each and the contour interval is 0.5 mag arcsec^{-2}. North is up and east to the left. As can be seen in Fig 1, there is no visible difference between the J- and H-band isophotes except for the innermost isophotes which are heavily affected by the atmospheric seeing. The shapes of the bulges of NGC 3412 and NGC 3941 are similar to each other. They are somewhat elongated with their position angles of major axes being different from those of the bars. There is no clear distinction between the bulge and the bar of NGC 3412 in their isophotes, but the weak variation of ellipticities and position angles, as shown in Fig. 2, are due to the presence of bar which ends near $r \sim 13''$. The bar of NGC 3941 is easily distinguishable from the bulge and disk in their isophotal maps.

(b) Luminosity Distribution

The surface brightness profiles, along with the profiles of ellipticity and position angle, derived from ellipse fittings to the observed isophotes are plotted in Fig. 2. We used the ellipse fitting program in IRAF/SPIRAL which is essentially the same as that described by Kent (1983). There seems to be no difference between the surface brightness profiles of J- and H-band for NGC 3412 (Fig. 2-(a)) but the J-band profile of NGC 3941 is steeper than the H-band profile in the bulge dominated region of $r < 10''$ (Fig. 2-(b)). The steep gradient in H-band makes the colors of the inner region bluer than the outer region. The bar of NGC 3412 is difficult to be recognized in the surface brightness profiles due to negligible bar luminosity but the bar of NGC 3941 is easily identified by a clear bump in the surface brightness profiles.

The profiles of ellipticity and position angle are presented in Fig. 2-(c) and (e) for NGC 3412 and Fig. 2-(d) and (f) for NGC 3941, respectively. In general there is no big difference in the radial variations of ellipticities and position angles in different passbands except for those at $r > 25''$ in NGC 3412 and at $r < 5''$ in NGC 3941. As shown in Fig. 2-(c) and (d) the mean ellipticity of the bulge of NGC 3412 is ≈ 0.2 with little variation along the radius while the ellipticity of NGC 3941 varies smoothly from 0.2 to 0.4 in the bulge with a mean value of ~ 0.3. The reason for the change of the bulge ellipticities in NGC 3941 is due to the bar luminosity which dominates the observed luminosity near $r \sim 20''$.

The bulges of NGC 3412 and NGC 3941 have been classified as triaxial because of the isophotal twists in the JHK images (Shaw et al. 1995). The smooth variation of position angles of NGC 3941 shown in Fig. 2-(f) indicates that the bulge of NGC 3941 is triaxial. But if we consider that the position angle of the bulge of NGC 3941 is similar to that of the disk, there is a possibility of an oblate spheroid for the bulge of NGC 3941. Because Ann (1995) took into account the misalignments between three components (bulge, disk, and bar) together, he classified the bulge of NGC 3941 as an oblate spheroid. The variation of position angles of NGC 3412 in Fig. 2-(e) is more complicated. But the behavior resembles the third type of isophotal twists defined by Wozniak et al. (1995), *barred plus twisted isophotes*, which is thought to be caused by bar and triaxial bulge.

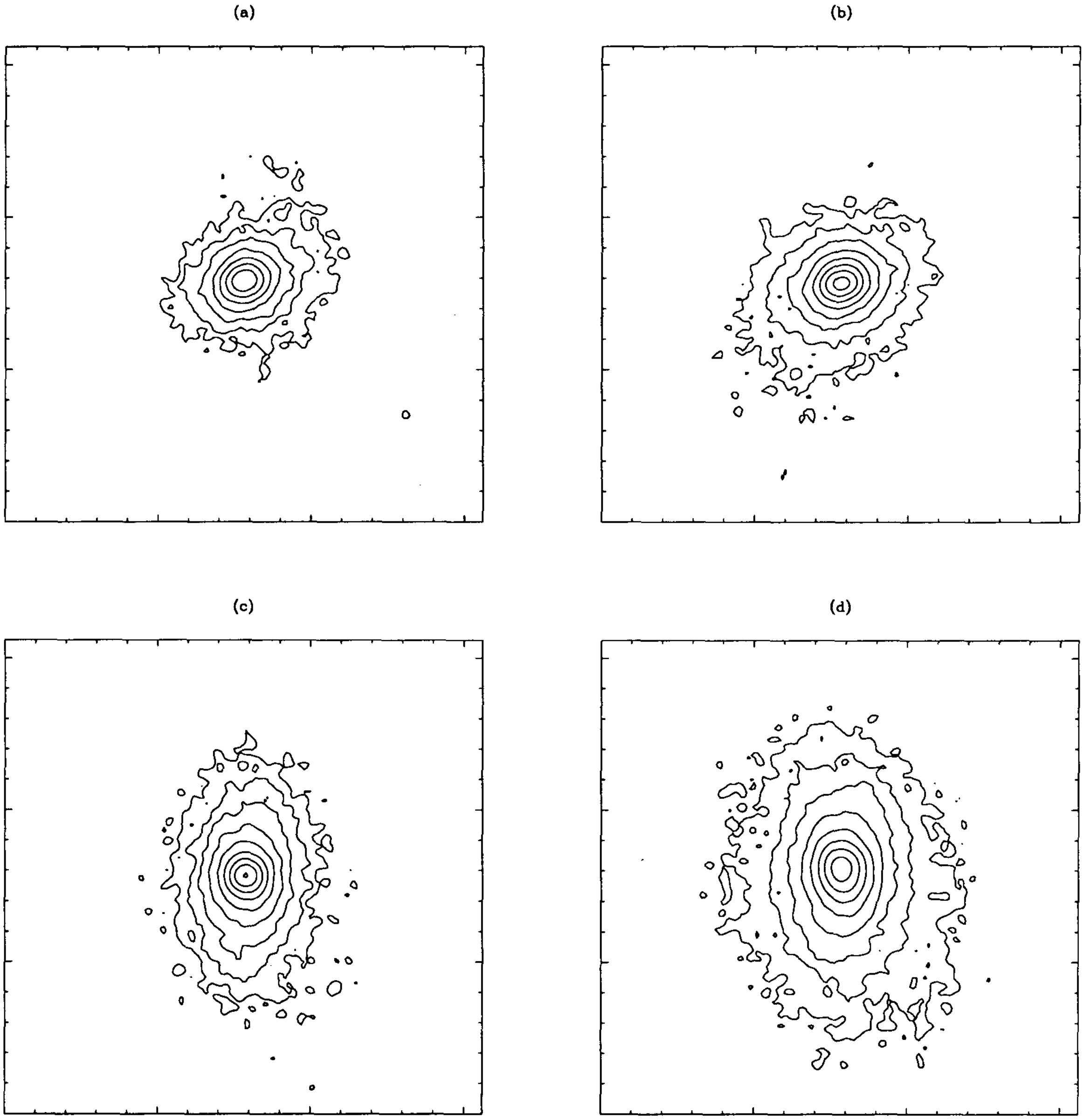

Fig. 1.— The *J*- and *H*-band isophotal maps of NGC 3412 (a, b) and NGC 3941 (c, d). *J*-band images are in the left panels and *H*-band images are in the right. The outermost contours are 18.5 mag arcsec^{-2} for *J*-band and 18.0 mag arcsec^{-2} for *H*-band, respectively.

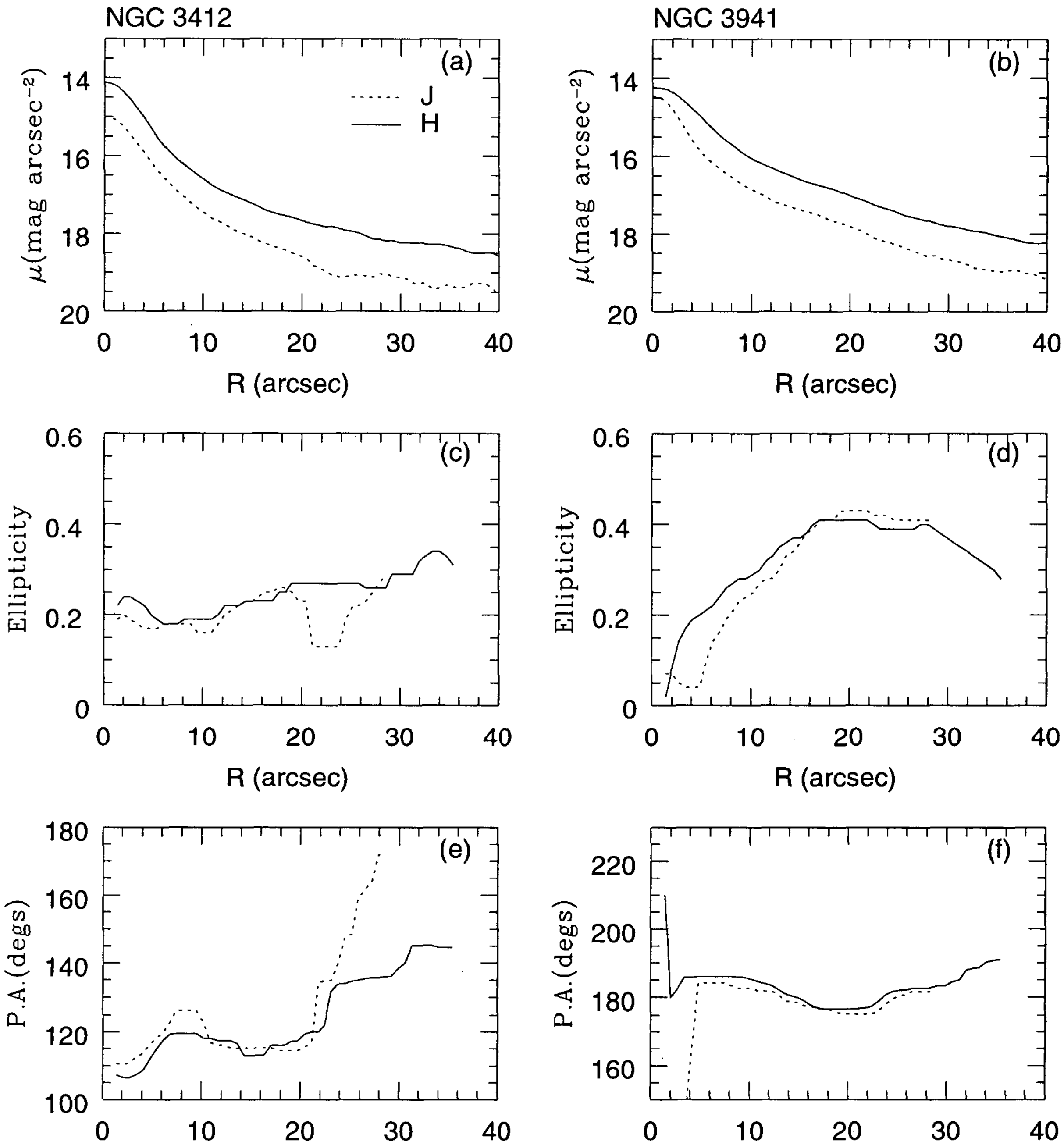

Fig. 2.— Profiles of surface brightness, ellipticity and position angle (P.A.) from ellipse fittings. The profiles of NGC 3412 are in the left panels and those of NGC 3941 are in the right panels.

Table 2. Effective radius and Effective brightness of the bulges of NGC 3412 and NGC 3941

Galaxy		r_e	μ_e	Galaxy		r_e	μ_e
N3412	J	13.8	18.12	N3941	J	28.1	18.82
	H	11.5	16.95		H	31.6	18.14

We determined the effective radius (r_e) and the effective surface brightness (μ_e) of the bulges of NGC 3412 and NGC 3941 by fitting the observed profiles to the de Vaucouleurs' $r^{1/4}$-law. We summarize the derived scale parameters in Table 2. The mean effective radius of the bulge of NGC 3412 is less than half of NGC 3941. Because both the isophotal radii and the distances of NGC 3412 and NGC 3941 inferred from the radial velocities in Table 1 are nearly the same, the bulge of NGC 3412 is intrinsically more centrally concentrated than that of NGC 3941. The bar luminosity might affect the scale parameters, especially in NGC 3941. However, the difference of the bulge scale lengths seems to be real because these parameters were determined where the bulge luminosities dominate the observed luminosity profiles. The small differences in the effective radii of the bulges in different passbands seem to be due to photometric errors.

(c) Color Profiles

Fig. 3 shows the $J-H$ color profiles along the major- and minor axes, together with the mean color profiles of the concentric annuli whose radii are defined as $r = \sqrt{r_1 r_2}$ where r_1 and r_2 are the radii of the inner and outer annuli, respectively. General trend of the three color profiles are similar to each other with some fluctuations due to low signal-to-noise ratio of the photometry. $J-H$ color of the nuclear region of NGC 3412 is not much different from that of the surrounding region. But it is redder than that of the bar ($\Delta(J-H) \approx 0.1$ mag). This color distribution is inconsistent with the photometry of Shaw et al. (1995) who showed that NGC 3412 has a blue nucleus which is 0.14 mag bluer than the surrounding region. Because of the probable errors in the zero point calibrations, the difference between the nuclear colors of the present photometry and those of Shaw et al. (1995) is quite plausible, but the opposite trend of the color variation along the radius is difficult to explain unless the photometric errors are very large. Our $J-H$ color of the bulge of NGC 3412 (~ 0.7) is similar to that of the mean $J-H$ color (0.78 ± 0.03) of bulges of ordinary spirals (Glass 1984).

The color profile of NGC 3941 is very unusual in the sense that it shows a very blue nucleus with a steep gradient inside $r \sim 8''$ with the largest gradient along the major-axis profile. This blue nucleus of NGC 3941 was not observed in the JHK photometry of Shaw et al. (1995) although their photometry shows that the nuclear color of NGC 3941 ($J-H = 0.53$) is somewhat bluer than that of the mean color (0.58 ± 0.07) of the blue nuclei galaxies.

IV. DISCUSSION AND SUMMARY

We analyzed the bulge morphology of two barred galaxies NGC 3412 and NGC 3941 by near-infrared photometry. The present photometry shows elongated bulges of both of the galaxies with a mean ellipticity of ~ 0.2. There are misalignments between the major axes of the bulges and bars, indicating that their bulges are triaxial. However, as noted by Ann (1995), there is a possibility of an oblate spheroid for the bulge of NGC 3941 because the position angle of the bulge is similar to that of the disk.

The bulge of NGC 3412 is more centrally concentrated than that of NGC 3941. The small bar and centrally concentrated triaxial bulge of NGC 3412 may suggest that the triaxial bulge is the result of bar dissolution. Recent N-body simulations of Norman, Sellwood, & Hasan (1996) showed that centrally concentrated bulges can destroy bars if the central mass is larger than 5 % of the total mass. Because our photometry does not extend to the outer parts of the galaxy, the mass fraction of the bulge of NGC 3412 can not be determined by the present photometry. However, it is quite plausible that the mass inside the centrally concentrated bulge is larger than that required for the bar dissolution if we consider the morphological type of NGC 3412 is SB0.

The $J-H$ color of the nuclear region of NGC 3941 is ~ 0.3 mag bluer than those of the surrounding regions. Blue nuclei similar to the nucleus of NGC 3941 have been observed for $\sim 70\%$ of 32 barred galaxies (Shaw et al. 1985). Their sample includes NGC 3412 and NGC 3941. But their photometry gives a normal nucleus for NGC 3941 and a blue nucleus for NGC 3412. This is opposite to the present result. We do not know the reason for the discrepancy between our photometry and that of Shaw et al. (1995). However, if the blue nucleus of NGC 3941 is real, it might be caused by the young stellar populations which are formed by the gas driven by the bar of NGC 3941. Recent SPH simulations show that strong bars are very effective to drive gas inflow which leads to burst of star formations (Friedli & Bens 1993; Ann & Kwon 1996). If the isophotal twists observed in the bulge of NGC 3941 are caused by the gas inflow which leads to the burst of star

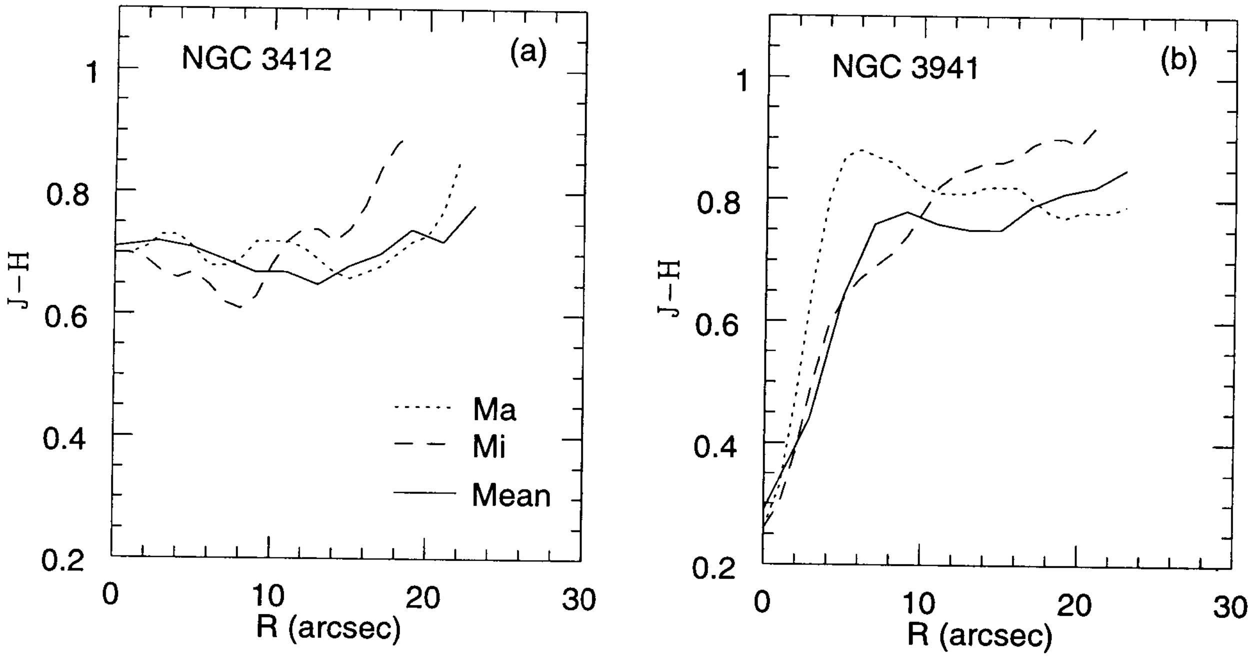

Fig. 3.— Color profiles of NGC 3412 and NGC 3941. Notice the blue nucleus of NGC 3941.

formation that results in the blue nucleus, the bulge of NGC 3941 is triaxial regardless of the similarity of the position angles of the bulge and disk.

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