Photometric parameters of edge-on galaxies from 2MASS observations

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Abstract.
To analyze the vertical structure of edge-on galaxies, we have used images of a large uniform sample of flat galaxies that have been taken during the 2MASS all-sky survey. The photometric parameters, such as the radial scale length, the vertical scale height, and the deprojected central surface brightness of galactic disks have been obtained. We find a strong correlation between the central surface brightness and the ratio of the vertical scale height to the vertical scale length: the thinner the galaxy, the lower the central surface brightness of its disk. The vertical scale height does not increase systematically with the distance from the galaxy center in the frames of this sample.

Key words. galaxies: structure – galaxies: photometry

1. Introduction
The study of edge-on galaxies provides a unique possibility to obtain information about vertical structure in galactic disks. Beginning with the papers of van der Kruit & Searle (1981a, 1981b, 1982), the investigation of edge-on galaxies continues today in optical bands (see van der Kruit 2001 and references therein) as well as at radio wavelengths (Matthews et al., 1999, van der Kruit et al., 2001). These studies help us to understand the laws governing the distribution of stellar and gaseous components of disks, and shed light on the role of dark halos in the evolution of spiral galaxies.

The main difficulty in studying edge-on disks in the optical is the need to take into account internal extinction by dust inside the disks. Extinction values can be enormous in the plane of a galaxy (of the order of a few tens of magnitudes for our Galaxy) and even far outside the plane they are substantial (see Xilouris et al., 1999). This is why it is preferable to use red and infrared data to investigate the structure of edge-on galaxies.

The 2MASS (Two Micron All Sky Survey) image library provides a sample of edge-on galaxies with near-infrared photometric data. Unfortunately the exposure time for 2MASS objects was too small to image the external parts of spiral galaxies, but it allows us to study the structures of their thin disks.

In this paper we use 2MASS data to obtain information about photometric parameters of stellar disks: their radial scale length, vertical scale height and deprojected central surface brightness for as many galaxies as possible. We choose the infrared photometric band $K_s$ for this study as it is the 2MASS band least influenced by dust extinction.

2. Sample of galaxies
The data from the 2MASS Public Release Image Server were used (see Nikolaev et al., 2000 for details of the images). All images and calibration data were collected using the web-based interface provided by the NASA/IPAC Extragalactic Database (http://irsa.ipac.caltech.edu/applications/2MASS/ReleaseVis/). Image tiles containing objects from the Revised Flat Galaxy Catalog (Karachentsev et al., 1999, hereafter RFGC) were chosen for this analysis. This gives some guarantee that the galaxies chosen all have thin and highly-inclined disks.

Our initial sample included more than 700 objects from the RFGC catalog which had already been detected in 2MASS survey. An examination of these images shows that there are only 153 objects whose major axes, $A$, span more than 40'' (in $K_s$ filter). We note that this value is related to the visible size of objects shown in the 2MASS...
frames. Such a widely used value as the isophotal diameter $D_{25}$ is generally about three times greater than the maximum size of the same objects in $K_s$ frames. Flat galaxies that have a value of $A$ close to 40° are marginally acceptable for the present analysis. The most critical parameter for the vertical structure analysis is the object size in the vertical direction i.e. parallel to the minor axis. Galaxies with $A < 40°$ do not allow us to analyze clearly the vertical cuts.

Finally, we refined this sample to a subsample consisting of 60 flat galaxies whose major axis size is more than 1′. Galaxies in this subsample seem to be more reliable for our analysis due to bigger angular diameter and will be examined together with the main sample of 153 galaxies to look for a possible difference in photometric parameters between the main sample and the subsample. This allows us to estimate possible systematic errors caused by the small size of some objects.

3. A method for obtaining the radial scale length, the vertical scale height and the central surface brightness of stellar disks

We follow the classic way to investigate the vertical structure of edge-on disks in spiral galaxies (van der Kruit & Searle, 1981a, 1981b, de Grijs & van der Kruit, 1996). It allows us to trace the behavior of the scale height at different distances from the center of the galaxy analyzing each photometric cut separately. In previous studies roughly ten cuts were made parallel to the minor axis of each galaxy, and a few parallel to its major axis.

In this paper we analyze a few tens of cuts spaced at equal intervals parallel to the minor axis of the disk. To estimate the radial scale length and the central surface brightness we made two cuts parallel to the major axis located at a certain distance from the galactic plane, as in the plane the value of internal extinction remains relatively large even in the IR spectral range.

A preliminary inspection of each frame was made to make an initial guess at the position of galactic center, as well as at the approximate size and orientation of the ellipse outlining the visible size of a galaxy. The ellipse is drawn along the faintest isophote seen in the image. The cuts were done parallel to the major and the minor axes of the ellipse. The cuts parallel to the major axis were gradually shifted our away from the major axis (in both directions) by 12-15% of the minor axis size in order to examine the surface brightness profile along the major axis. The number of cuts parallel to the minor axis was chosen to be around 20-30, thus covering most of the disk. The 2MASS survey is not sensitive to the very faint parts of galaxies, so our results are related mostly to the thin stellar disks. Hence, emission from the thick stellar disk might be neglected near the galactic plane.

The equations used to fit the parameters of each cut assume an exponential law for the distribution of luminosity volume density in the radial direction $\rho_L(r)$ and an isothermal law for the distribution in the vertical direction. In this case a general form of surface brightness distribution $I$ on the plane of a sky $(X, Y)$ is

$$I(X, Y) = \int \rho_L(r, z) dl ,$$

where

$$\rho_L(r, z) = \rho_{Lo} \exp \left(-\frac{|r|}{R_e}\right) \sech^2 \left(\frac{|z|}{z_0}\right) ,$$

$r$ is the radial distance from the center of a galaxy, $z$ is the distance from the galactic plane, $z_0$ and $R_e$ denote the vertical scale height and the radial scale length respectively. Integration of $I(2)$ proceeds along the line of sight. One can find the deprojected central surface brightness $S_0$ by integrating $I(2)$ along the vertical axis.

In the first-order approximation we assume $z_0$ to be independent of radius $r$, as has been previously noted by many authors (see e.g. van der Kruit & Searle, 1981a, 1981b, de Grijs & Peletier, 1997). To take into account the radial variability of the vertical scale height, we must know a priori the form of $z_0(r)$. More generally, we can assume that $z_0$ is a monotonous function of $r$. Then, using our approximation we can determine whether $z_0$ varies significantly with radial distances or not.

We use Eq. $(1)$ by fixing the Y coordinate and drawing two cuts parallel to the major axis to obtain the values of $R_e$ and $S_0$. In a similar way, we fit the cuts drawn parallel to the minor axis to find the values of $z_0$. In this case we add a variable "shift term" $\delta Y$ to find the declination of the center of each cut from the galactic plane.

In this study we do not consider the possibility that some disks may not be 90°inclined, because we find that most objects from the RFGC catalog have inclinations that are close to 90°. A more detailed study that includes the non-90°inclined disks is problematic, since we usually do not see a dust layer on most of the 2MASS galactic images taken in the $K_s$-band.

While analyzing the radial surface brightness profiles, we exclude their central parts (typically 1/3 - 1/4 of the maximal extent of the radial profile) to decrease the influence of the bulge light on our results.

The smearing effect caused by the Earth’s atmosphere affects the values of the measured scales by increasing the value of the scale height. To take this effect into account, we convolved the fitting functions with a gaussian. The mean FWHM value of the PSF was about 3′′ during the survey so we have chosen 3′′as the FWHM of the gaussian. Finally the functions were fitted to the extracted profiles by the least-squares method.

The flux calibration of the central deprojected surface brightnesses $S_0$ is available from equations given by Nikolaev et al. (2000). Finally, we corrected the $S_0$ values for the Galactic extinction (using the data from LEDA, the Lyon-Meudon extragalactic database).

We analyzed the set of cuts parallel to the major and minor axes for each galaxy in our 2MASS sample and
obtained the values of $S_0$, $R_e$, $z_0(r)$, and $\delta Y$ as the output. The value of $Y_0$ was used to correct the position angle of the ellipse outlining the faintest isophote in the image of a galaxy, if it was needed, and to correct the final value of $z_0$ for each distance from the center $r$. Finally, we take the value of $z_0$ as the median value of all scale heights and the value of $R_e$ as the average value of all scale lengths for each galaxy. The averaging of scale length/height allow us to avoid the influence of stars and bad pixels projected onto the images on the final values of $R_e$ and $z_0$.

The output photometric parameters are presented in Table 1. It contains (1) the name of the galaxy according to RFGC catalog, (2) the distance in Mpc adopted in our paper, (3) the radial scale length in kpc, (4) the central surface brightness reduced to the face-on inclination in mag/arcsec$^2$, (5) the vertical scale height in kpc, and (6) the label "x" marking the galaxy that belongs to the subsample.

### 4. Results and Discussion

Fig. 1 shows the relation between the corrected central surface brightness $S_0$ and the ratio $z_0/R_e$ of the scale height to the scale length of a disk. Open squares in Fig. 1 denote our main sample of galaxies. Filled squares show the subsample of galaxies. The linear fit gives the equation $z_0/R_e = 1.30 - 0.059 \cdot S_0$ for the subsample of 60 galaxies in Fig. 1.

As it is seen in Fig. 1, there is a strong correlation between $S_0$ and $z_0/R_e$. Thicker disks have higher values of central surface brightness, and vice versa. The scatter in the points for the the main sample is larger than the scatter for the subsample. This indicates a typical uncertainty in $z_0/R_e$ for the subsample of 60 galaxies in Fig. 1. Nevertheless, the correlations between these values for the more resolved galaxies gives us hope for even better results when the higher resolution photometric data will be available.

The systematic difference between galaxies of different sizes (open versus filled squares) is well seen in Fig. 1. It reflects the overestimation of $z_0$ for the faintest galaxies of the main sample.

As was noted by Gerritsen & de Blok (1999), the low surface brightness galaxies (LSB) must be relatively thinner than the normal (HSB) galaxies. The most natural explanation of this feature is that a dark halo does contribute a substantial part of the mass in LSB galaxies (de Blok & McGaugh, 1997). A shallower central part of the rotation curve is a typical feature of LSB galaxies, which requires a large fraction of dark matter (van den Bosch et al., 2000). Fig. 1 shows that the values of deprojected central surface brightness of disks span about 2.5 magnitudes (for the subsample of galaxies). This agrees well with the observational data published by de Jong (1996a), Tully & Verheijen (1997) for almost face-on disks. These authors show that the typical difference in $S_0$ values between LSB and HSB galaxies is of the order of 2 magnitudes.

From the $K_s$-band central surface brightness of 18.2 mag/arcsec$^2$ and the $B$-band central surface brightness of 21.65 mag/arcsec$^2$ (Freeman, 1970) we infer the $(B-K_s) \approx 3.5$ for the central parts of deprojected face-on disks. This is in good agreement with the values of $S_0$ in Fig. 1. Fainter disks in Fig. 1 have $S_0$ values that differ from the typical Freeman value in $K_s$-band by 1.5 - 2 magnitudes. These faint disks appear to be the LSB disks in our sample.

Using galactic distances based on radial velocities reduced for Galactic Standard of Rest movement ($V_{GSR}$ taken from LEDA), we compare the linear values of $z_0$ and $R_e$ for galaxies with different central surface brightnesses (see Fig. 1). We use a Hubble constant of 75 km s$^{-1}$Mpc$^{-1}$ throughout this paper. As can be seen in Fig. 1, neither the linear value of $R_e$ nor that of $z_0$ tends to show a systematic difference between LSB and HSB disks. Note that the errors in distances lead to additional scatter of the points in Fig. 1 especially for nearby galaxies. A more sophisticated analysis of distance-related values based on new distance estimates is needed. This question will be addressed in the next paper.

Nevertheless, the correlations between $S_0$ and each of scales $z_0$ and $R_e$ (Fig. 1) are much worse than the correlation between $S_0$ and the ratio of scales $z_0/R_e$ (Fig. 1). It implies that the latter correlation is based on a more sig-
significant physical foundation than the correlations between \( S_0 \) and each of scales \( z_0 \) and \( R_e \). A pronounced correlation between \( S_0 \) and \( z_0/R_e \) implies the importance of dark halos in galaxies with low values of \( S_0 \). The gravity of the halo does not let the disk grow thicker in this case.

Eleven galaxies from our sample have the scales measured and published by Barteldrees & Dettmar (1994) and Schwarzkopf & Dettmar (2000). Four of them were observed in the K’-band, which is very close to \( K_s \) where our estimates have been done. Fig. 3 shows a comparison of radial scale lengths (upper frame) and vertical scale heights (lower frame) made for these cases. Distance-dependent values for galaxies from other papers are corrected to our distance scale. Filled triangles denote the scales that have been obtained using the K’-band data. Open triangles are related mostly to R-band observations. Solid lines show the case of the equality of the scales.

& Searle (1982) using photographic plates in the J-band (close to Johnson’s B). Using distances to galaxies from the present paper (3.6 and 10.9 Mpc respectively) we can compare our scale lengths/scale heights. The published values are 1.87/0.41 kpc and 5.65/0.82 kpc after reducing to our distance scale, whereas our values are 1.23/0.33 kpc and 3.35/0.49 kpc respectively. The values are of the same order and a systematic difference is expected because of usually shorter scales in near-infrared filter bands. Finally, the scales for another galaxy, UGC 11194, were found using I-band observations and published by Bizyaev (2000). The scales are 4.48/0.98 kpc in contrast to 5.04/0.90 kpc found in this paper. The scales for the same galaxy were published by Reshetnikov & Combes (1997). After correcting to our distance scale they are 4.0/1.15 kpc.

In spite of the low accuracy achieved for each individual cut, we are able to estimate roughly the radial trend of \( z_0(r) \). To do so, we exclude a few values of scale height that deviate from the general trend by more than 3 \( \sigma \). We fit the values of \( z_0 \) to a linear function of \( r \). The histogram in Fig. 4 shows the results of the fitting. The gradient
Fig. 4. The radial gradient of the vertical scale height $dz_0/dr$ for our sample of galaxies. The average value of $dz_0/dr$ is very close to zero. The standard deviation of $dz_0/dr$ is equal to 0.0063. The subsample of galaxies is highlighted by the filled part of histogram.

$dz_0/dr$ is presented in dimensionless values. The subsample of galaxies is shown by the filled part of the histogram in Fig. 4.

As one can see in Fig. 4, the average value of $dz_0/dr$ is very close to zero (0.001), which is in agreement with the conclusions of many previous studies (see previously cited references). The subsample of galaxies has an average value of $dz_0/dr=0.0003$ (i.e. zero). The standard deviation of $dz_0/dr$ in Fig. 4 is equal to 0.006 for the whole sample and 0.005 for the 60 largest galaxies in this sample. It gives a 10% change of the measured scale height on distances of 3.5 $R_e$ from the center, i.e. at the very edge of a stellar disk adopting a typical value of $z_0/R_e$ from Fig. 1. Note that the real change of $z_0$ along the radius needed to produce the 10% trend may be 2-3 times more significant due to projection of different parts of the disk on the line of sight.

5. Conclusions

We analyzed the vertical and the radial distributions of near-infrared surface brightness in disks of flat galaxies observed during the 2MASS survey. A strong dependence of the ratio $z_0/R_e$ of the vertical scale heights to the radial scale lengths on the deprojected central surface brightness $S_0$ is inferred. Galaxies with lower central surface brightnesses look thinner and have lower values of $z_0/R_e$. The linear value of the radial scale length appear to be independent of the central surface brightness, the same conclusion is true for the vertical scale height. We can also conclude that the vertical scale height of thin stellar galactic disks is almost independent of radius for galaxies in our sample and has almost the same value over a wide range of distances from the center.

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Table 1. Photometric parameters of disks of galaxies.

| Name | D (Mpc) | $R_e$ (kpc) | $z_0$ (mag/kpc) | $z_0$ (kpc) | Note$^1$ |
|------|---------|-------------|-----------------|-------------|---------|
| 95   | 13.10   | 1.45        | 19.50           | 0.26        | x       |
| 139  | 72.34   | 3.18        | 18.59           | 0.95        |         |
| 176  | 72.01   | 5.66        | 18.78           | 1.00        | x       |
| 183  | 69.80   | 8.11        | 19.43           | 0.92        | x       |
| 206  | 62.16   | 1.94        | 16.47           | 0.77        |         |
| 282  | 91.56   | 3.69        | 18.15           | 0.93        |         |
| 355  | 74.42   | 4.79        | 18.96           | 0.85        |         |
| 363  | 75.23   | 5.36        | 18.20           | 1.02        | x       |
| 420  | 74.57   | 3.10        | 17.28           | 0.87        | x       |
| 444  | 122.18  | 6.10        | 18.41           | 1.06        |         |
| 485  | 110.64  | 5.45        | 19.13           | 1.16        |         |
| 504  | 50.76   | 4.80        | 18.39           | 0.72        | x       |
| 517  | 71.07   | 5.19        | 19.72           | 1.02        |         |
| 507  | 53.84   | 2.38        | 18.71           | 0.63        | x       |
| 538  | 26.71   | 1.66        | 18.73           | 0.48        | x       |
| 544  | 84.44   | 3.33        | 19.71           | 0.85        |         |
| 551  | 148.94  | 5.02        | 17.56           | 1.78        |         |
| 561  | 145.61  | 4.70        | 17.56           | 1.39        |         |
| 586  | 56.42   | 2.04        | 17.64           | 0.74        |         |
| 603  | 70.77   | 2.24        | 16.79           | 0.98        |         |
| 609  | 84.09   | 4.60        | 17.53           | 1.57        | x       |
| 642  | 34.56   | 2.55        | 18.34           | 0.42        | x       |
| 653  | 162.75  | 17.61       | 19.43           | 1.71        |         |
| 671  | 143.69  | 8.18        | 18.13           | 1.92        |         |
| 702  | 36.65   | 1.70        | 18.89           | 0.43        |         |
| 722  | 24.11   | 2.23        | 18.92           | 0.41        | x       |
| 744  | 124.66  | 4.96        | 18.12           | 1.14        |         |
| 757  | 131.95  | 5.51        | 18.10           | 1.54        |         |
| 765  | 121.79  | 6.06        | 17.68           | 1.69        | x       |
| 826  | 115.75  | 7.66        | 19.05           | 1.67        |         |
| 882  | 80.19   | 3.09        | 17.55           | 0.80        | x       |
| 895  | 15.23   | 1.45        | 19.26           | 0.38        | x       |
| 902  | 58.95   | 2.71        | 17.85           | 0.86        | x       |
| 914  | 125.78  | 4.03        | 18.17           | 0.98        | x       |
| 1047 | 36.33   | 1.82        | 18.74           | 0.51        | x       |
| 1049 | 13.39   | 0.96        | 17.18           | 0.22        | x       |
| 1128 | 51.89   | 4.41        | 17.75           | 0.70        | x       |
| 1135 | 63.82   | 2.30        | 18.45           | 0.53        | x       |
| 1140 | 63.88   | 3.32        | 17.53           | 0.78        |         |
| 1143 | 58.62   | 3.73        | 18.90           | 0.76        | x       |
| 1159 | 85.70   | 6.78        | 18.46           | 1.50        | x       |
| 1167 | 52.15   | 3.37        | 18.59           | 0.71        | x       |
| 1194 | 29.44   | 2.30        | 17.75           | 0.64        | x       |
| 1206 | 32.57   | 1.84        | 17.69           | 0.39        | x       |
| 1244 | 41.43   | 4.79        | 18.64           | 1.09        | x       |
| 1263 | 63.54   | 3.34        | 18.01           | 0.75        |         |
| 1329 | 54.63   | 2.62        | 19.41           | 0.68        |         |
| 1339 | 73.42   | 7.83        | 18.67           | 1.13        | x       |
| 1349 | 56.14   | 2.69        | 17.15           | 0.79        | x       |
| 1421 | 19.98   | 1.76        | 17.68           | 0.40        | x       |
| 1431 | 58.34   | 5.42        | 17.51           | 1.38        | x       |
| 1459 | 102.94  | 3.14        | 17.89           | 0.88        | x       |

$^1$ - "x" means part of the more reliable subsample (see text).
Table 1, Continue

|   |     |     |     |     |
|---|-----|-----|-----|-----|
| 2860 | 28.59 | 1.93 | 17.57 | 0.56 | x |
| 2945 | 153.26 | 9.95 | 18.77 | 1.77 |
| 2946 | 10.90 | 3.35 | 18.25 | 0.49 | x |
| 2966 | 92.63 | 4.74 | 18.46 | 0.95 |
| 2994 | 47.61 | 4.31 | 17.08 | 1.65 | x |
| 3004 | 127.28 | 6.29 | 18.11 | 1.75 |
| 3006 | 43.30 | 3.04 | 18.79 | 0.58 |
| 3085 | 62.95 | 2.55 | 17.80 | 0.67 |
| 3094 | 120.43 | 8.03 | 18.15 | 1.56 | x |
| 3098 | 132.44 | 4.81 | 18.13 | 1.59 |
| 3106 | 125.47 | 5.45 | 18.03 | 1.61 |
| 3114 | 32.16 | 1.50 | 18.42 | 0.50 |
| 3227 | 115.45 | 5.17 | 18.04 | 1.42 |
| 3240 | 128.98 | 5.04 | 17.74 | 1.47 |
| 3313 | 56.19 | 2.54 | 17.82 | 0.80 |
| 3352 | 72.73 | 3.25 | 18.14 | 0.94 |
| 3378 | 75.42 | 2.94 | 18.24 | 0.76 |
| 3430 | 59.13 | 4.99 | 18.37 | 1.03 |
| 3455 | 65.01 | 2.93 | 18.30 | 0.68 |
| 3477 | 143.56 | 6.44 | 18.44 | 1.86 |
| 3480 | 150.33 | 7.31 | 18.37 | 1.67 |
| 3507 | 78.03 | 3.91 | 17.59 | 1.30 | x |
| 3580 | 72.82 | 5.30 | 18.86 | 1.01 | x |
| 3614 | 83.47 | 4.22 | 18.88 | 0.80 |
| 3658 | 109.38 | 4.51 | 17.63 | 1.28 |
| 3762 | 117.38 | 5.21 | 17.42 | 1.46 |
| 3793 | 46.09 | 3.70 | 18.13 | 0.68 | x |
| 3863 | 77.13 | 5.96 | 18.07 | 1.07 | x |
| 3903 | 35.29 | 3.23 | 18.43 | 0.59 | x |
| 3926 | 67.84 | 5.05 | 18.11 | 0.90 | x |
| 3984 | 117.45 | 6.50 | 19.60 | 1.07 |
| 3985 | 89.81 | 3.03 | 17.81 | 0.99 |
| 4004 | 99.54 | 6.95 | 18.64 | 1.23 | x |
| 4013 | 43.43 | 11.09 | 20.69 | 0.51 |
| 4043 | 99.73 | 3.54 | 17.21 | 1.13 |
| 4051 | 90.88 | 3.03 | 18.29 | 0.97 |
| 4076 | 97.13 | 4.46 | 17.83 | 0.93 | x |
| 4078 | 118.28 | 5.77 | 17.69 | 1.15 | x |
| 4092 | 93.99 | 2.56 | 17.55 | 0.83 |
| 4103 | 145.16 | 5.91 | 17.60 | 1.46 |
| 4106 | 98.73 | 4.11 | 17.60 | 1.22 |
| 4110 | 82.41 | 15.53 | 16.35 | 4.18 |
| 4136 | 70.31 | 2.32 | 17.71 | 0.89 |
| 4165 | 92.36 | 3.89 | 17.38 | 1.10 |
| 4171 | 101.53 | 5.39 | 17.87 | 1.24 |