Abstract. We study the effects of dusty spiral arms on the photometric properties of disk galaxies using a series of 2D radiative transfer models, approximating the arms with axially symmetrical rings. We find that dusty arms, as well as dusty disks, have a significant influence on the aperture photometry and surface brightness profiles altering colors of model galaxies. We suggest that, in addition to the conventionally modeled diffuse absorbing layers or disks, the dusty arms should be taken into account in spiral galaxy extinction studies.

Key words: ISM: dust, extinction – galaxies: spiral – galaxies: ISM – galaxies: photometry

1. INTRODUCTION

Since the pioneering work on the extinction effects in galaxies by Holmberg (1958) through the recent papers (Disney, Davies & Phillips 1989; Kodaira, Doi & Shimasaku 1992; Corradi, Beckman & Simonneau 1996 and others referred therein) it has been assumed for modeling that the absorbing matter is smoothly distributed in the geometry of layers parallel to the stellar disk. In particular, various inclination effects have been interpreted using the absorption-layer models, leading to partly contradicting inferences about the opaqueness of galaxy disks (see Valentijn 1990; Burstein, Haynes & Faber 1991; Huizinga & van Albada 1992; Davies & Burstein 1995). Conclusions of these statistical studies strongly depend on the studied galaxy samples which show a wide variety even among galaxies of a given morphological type. Kodaira & Yamashita (1996) analyzed edge-on Scd (T = 6) galaxies NGC 3556 and NGC 4244 and pointed out the contrasting nature between the two examples. The former is rich in dark-lane features and has a high index of $B_T - m_{FIR} = +1.48$, while the latter scarcely shows dark lanes and has a low index of $B_T - m_{FIR} = -0.3$. By applying exponential layer models for the stellar disk and the absorbing matter, the authors found that the central dust layer of NGC 3556 has an outer cut-off radius smaller than the stellar disk extent and opaque patches which may partly be due to spiral arms. We suspect that in NGC 3556 the dark arms may play a significant role in the total extinction in addition to the diffuse absorbing component.

Normally, in face-on galaxy images we ignore the spiral dark lanes because of
small cross-section on the galactic plane and of the assumed small height above the plane. However, Sofue (1987) and Sofue, Wakamatsu & Malin (1994) suggested that the spiral dark lanes in general may have vertical structures which reach high above the stellar disk. They investigated NGC 253 (Sc) and NGC 7331 (Sb) and found abundant dark structures rising from the spiral dark lanes up to a few kpc above the disk plane. By examining images of edge-on galaxies in the Hubble Atlas, similar structures are easily found for NGC 891 (Sb) and NGC 4631 (Sc). The four galaxies mentioned above all have a high index of $B_T - nFIR > 1.5$ according to RC3 (de Vaucouleurs et al. 1991), indicating enhanced star-formation activity (see Tomita, Tomita & Saito 1996 and references therein). Bosma et al. (1992) made velocity-profile analysis of NGC 891 using H I, CO and Hα lines, to find that the inner part of this galaxy is optically thick while the outer part is optically thin when seen at face-on. Huizinga & van Albada (1992) made the same conclusion for Sc galaxies in general. We are reminded that spiral arms often occupy a larger fraction of space in the inner part of disk galaxies than in the outer part. Block, Elmegreen & Wainscoat (1995) studied NGC 2841 in near IR to reveal underlying spiral dark lanes behind the amorphous smooth optical images.

These findings support the suspicion that the dark lanes may play a significant role in internal extinction of some disk galaxies. Corradi et al. (1996) in their photometric models of disk galaxies considered differences of stellar populations between the arm and the inter-arm regions, however, they adopted the layer geometry for dust distribution. Wainscoat et al. (1992) adopted a logarithmic spiral pattern in constructing a galaxy model for distribution of young massive stars, but an exponential layer model for absorbing matter. Misiriotis et al. (2000) have found that a double-exponential disk provides a very good fit for dusty spiral galaxies seen edge-on. Steep gradients and high contrasts between arm and inter-arm regions, apparent in face-on views of their model, possessing values of $R_{	ext{eff}}$ for dust and star distributions and up to 1/3 of the dust locked in spiral arms, are largely averaged over at high inclinations. Therefore, it is important to provide means to model the changes of the observed properties of galaxies in transition between edge-on and face-on orientations.

Strong color gradients, as well as large variations in disk flatness (scale-height to scale-length ratio, $Z_{\text{eff}}/R_{\text{eff}}$), are observed in most late-type galaxies. Furthermore, many objects display variable color gradients or their absence (“flat” color profiles), which can be related to their evolution stage or internal extinction properties (Reshetnikov, Dettmar & Combes 2003). Therefore, in order to establish validity limits of population synthesis model employment for computation of the radial color profiles, it is important to estimate the effects of dusty spiral arms on model galaxy color gradients (color excess profiles).

However, it should be stressed that a spiral pattern in galaxies is traced not only in the distribution of the interstellar medium, but also in the young stellar populations, i.e., the stellar arms. Their presence can significantly alter photometric properties of galaxies and, in order to compare model predictions with observations for local well resolved and distant semi-resolved or unresolved galaxies, the modeling procedure must take all these features into account. In this study we focus on the additional extinction effects, produced by dusty arms, on colors of stellar disk populations in spiral galaxies. Our aim is to estimate the possible range of magnitude of these effects, thus we choose rather extreme cases of the dusty disks and the dusty arms. Due to these simplifications, direct application
of our results for interpretation of the observations is strongly restricted to some specific cases, e.g., for galaxies in which energy, radiated by young stellar populations concentrated in spiral arms, does not dominate the total energy radiated by the disk stellar populations. However, the presented results can serve as a guide for the spiral galaxy extinction estimate in general.

In this paper we present the radiative transfer code and galaxy models employed (section 2), examine the galaxy inclination and dusty spiral arm effects on the surface brightness and color excess profiles of bulge-less (late type, Sc-Sd) spiral galaxies, relevant to the photometric galaxy survey and number count interpretation (section 3), and give brief conclusions.

2. RADIATIVE TRANSFER CODE AND MODEL GALAXIES

Realistic evaluation of dusty spiral arm influence on the observed photometric properties of disk galaxies has to be performed fully accounting for multiple light scattering events and presence of the dusty disk, possessing diffuse distribution of interstellar dust. To test these effects the radiative transfer problem has been solved for the eight model galaxies M1–M8 (Table 1), representing several star and dust distributions, using the Galactic Fog Engine code (Semionov & Vansevičius 2005c).

This code realizes an iterative ray-tracing algorithm in 2D axi-symmetrical geometry, allowing for a flexible definition of stellar and dust content distribution, producing intensity maps of the model under arbitrary inclination at a given set of wavelengths/passbands. Computations are performed within a cylinder, which is subdivided into a set of layers of concentric internally homogeneous rings of varying vertical and radial extent. This cylinder is then sampled using a set of adaptively chosen directions (rays), along which one-dimensional radiative transfer problems are solved. The number and placement of rays depends on stellar light and dust distribution. In the course of the first iteration the initial radiative energy of the system is separated into escaped, that directly reaches an external observer, absorbed by dust grains, and non-isotropically scattered (Semionov & Vansevičius 2005a) radiative energies. The solution is then repeated, substituting scattered radiative energy as the initial distribution for the next iteration, accumulating resulting escaped and absorbed radiative energies, until certain convergence criteria are met – either a fixed number of iterations is reached, or the remaining scattered radiative energy drops below the specified threshold. The Galactic Fog Engine has been carefully tested against several previously published radiative transfer codes (Witt, Thornson & Capuano 1992; Ferrara et al. 1999), and the results were found to be deviating by less than a few percent from the published values (Semionov & Vansevičius 2002).

Each model (see Table 1) was represented by a cylinder consisting of 35 concentric rings, subdivided into 49 layers, with radial and vertical extent of 6 and 2.5 stellar disk scale-lengths, \( R_{\text{eff}} \), respectively. The radiative transfer was evaluated using seven ray-tracing iterations, of which the first three were computed directly and the remaining four – using iteration scaling approximation (Semionov & Vansevičius 2005b). The radiative energy defect and the radiative energy remaining to be scattered after the last iteration were below 1% of the total emitted radiative energy in all cases.
Fig. 1. Diametral cross-section of the interstellar dust distributions in model galaxies. Panels (a) and (b) show the schematic cross-section of models with dusty disk and with both, a dusty disk and dusty rings, respectively. Shading represents varying relative dust mass density. Marked are the scale-length of stellar disk, $R_{\text{eff}}$, and the radial positions at which optical depths $\tau_{\text{disk}}$ and $\tau_{\text{ring}}$ are measured.

All models have identical stellar populations, distributed according to a double-exponential law:

$$\rho(R, Z) = \rho_0 \exp \left( -\frac{R}{R_{\text{eff}}} - \frac{|Z|}{Z_{\text{eff}}} \right),$$  

where $R_{\text{eff}}$ and $Z_{\text{eff}}$ are the scale-length and scale-height, respectively. To simulate the effect of dust residing in the galaxy disk and arms, extinction in the model galaxy was distributed in the dusty disk and dusty arms. Model galaxy schemes are shown in Figure 1 as $(R, Z)$ diametral cross-sections of the models with gray-scale tones indicating the relative density of the interstellar dust. Dusty disk extinction distribution follows a double-exponential law with varying scale-length, $R_{\text{eff}}^d$, and scale-height, $Z_{\text{eff}}^d$, for different models. Central optical depth in $V$-band (measured to the central plane of the model galaxy in the direction perpendicular to it) is set to $\tau_{\text{disk}}^V = 5$ for all models.

The dusty arm (“ring”) extinction distribution in the model galaxy is represented by three identical dusty rings situated at radial distances $R = 1.25, 2.5$ and $3.75R_{\text{eff}}$ from the model axis. Each ring has a radial extent of $0.45R_{\text{eff}}$ and consists of three radial zones of equal width of $0.15R_{\text{eff}}$. The total optical depth of the zones in the $V$-band (measured to the central plane of the model galaxy in the direction perpendicular to it) is set to $\tau_{\text{ring}}^V = 5$ (inner zone), $2$ (middle zone) and $1$ (outer zone), respectively (see Figure 1). Vertical dust distribution within each zone is described by the one-dimensional exponential law

$$\rho(R, Z) = \rho_0 R \exp \left( -\frac{|Z|}{Z_{\text{eff}}^d} \right),$$  

where $R_{\text{eff}}^d$ and $Z_{\text{eff}}^d$ are the scale-length and scale-height of the dusty disk and dusty arms, respectively.
assuming identical scale-heights, \( Z_{\text{eff}} \), for the dusty rings and the dusty disk for each model.

Both, disk- and ring-distributed dust, have the same optical properties, computed using the Laor & Draine (1993) model, approximating Milky Way galaxy type extinction, using a mixture of graphite and silicate grains in the proportion of 0.47 to 0.53 (Mathis, Rumpl & Nordsiek 1977) and grain size distribution following the power law \( a^{-3.5} \) possessing lower and upper cut-off radii \( a_{\text{min}} = 0.005 \) \( \mu \)m and \( a_{\text{max}} = 0.25 \) \( \mu \)m.

The geometric parameters of star and dust distributions for the model galaxies M1–M8, discussed in this work, are presented in Table 1. All models have identical stellar populations, described using the scale-length, \( R_{\text{eff}} \), and -height, \( Z_{\text{eff}} \). To simulate the commonly used relative star-to-dust test distributions the respective scale-length, \( R_{d\text{eff}} \), and -height, \( Z_{d\text{eff}} \), of the dusty disk were varied, producing “standard” (\( R_{d\text{eff}} = R_{\text{eff}} \) and \( Z_{d\text{eff}} = Z_{\text{eff}} \); M1 and M5), “thin” (\( R_{d\text{eff}} = R_{\text{eff}} \) and \( Z_{d\text{eff}} = 0.5 Z_{\text{eff}} \); M2 and M6), “thick” (\( R_{d\text{eff}} = R_{\text{eff}} \) and \( Z_{d\text{eff}} = 2.0 Z_{\text{eff}} \); M3 and M7), and “wide” (\( R_{d\text{eff}} = 2.0 R_{\text{eff}} \) and \( Z_{d\text{eff}} = Z_{\text{eff}} \); M4 and M8) models. Models M1–M4 represent pure disks, similar to bulge-less SxxMExx models in Ferrara et al. (1999), with dust extinction present only in a form of a double-exponential law with constant central optical depth, \( \tau_{\text{disk}} \), for all cases, while models M5–M8 additionally contain the dusty arms with the same maximum optical depth, \( \tau_{\text{ring}} \), for all rings. The resulting total dust mass, \( M_{\text{d}} \), in Solar mass units, required to produce this amount of opacity, is given in Table 1.

### Table 1. Parameters of the studied model galaxies.

| Model | \( R_{\text{eff}} \) | \( Z_{\text{eff}} \) | \( R_{d\text{eff}} \) | \( Z_{d\text{eff}} \) | \( \tau_{\text{disk}} \) | \( \tau_{\text{ring}} \) | \( \log M_{\text{d}} \) |
|-------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| M1    | 2.0                 | 0.2                 | 2.0                 | 0.2                 | 5                   | 0                   | 7.55                |
| M2    | 2.0                 | 0.2                 | 2.0                 | 0.1                 | 5                   | 0                   | 7.55                |
| M3    | 2.0                 | 0.2                 | 2.0                 | 0.4                 | 5                   | 0                   | 7.55                |
| M4    | 2.0                 | 0.2                 | 4.0                 | 0.2                 | 5                   | 0                   | 8.06                |
| M5    | 2.0                 | 0.2                 | 2.0                 | 0.2                 | 5                   | 5                   | 8.01                |
| M6    | 2.0                 | 0.2                 | 2.0                 | 0.1                 | 5                   | 5                   | 8.01                |
| M7    | 2.0                 | 0.2                 | 2.0                 | 0.4                 | 5                   | 5                   | 8.01                |
| M8    | 2.0                 | 0.2                 | 4.0                 | 0.2                 | 5                   | 5                   | 8.25                |

For all models we have computed 1000×1000 pixel images with a scale of 0.0125\( R_{\text{eff}} \) per pixel at the wavelengths corresponding to the \( B \), \( V \) and \( K \)-bands for model galaxy inclinations between 0° and 90° with a step of 5°. We have performed surface photometry of these images using concentric apertures with ellipticity determined from the model inclination, the apertures being centered on the geometric center of the model galaxy image. Magnitudes and color excesses in growing apertures, differential azimuthally-averaged surface brightness and color excess profiles, as well as various cross-sections of the model galaxies, were derived and analyzed.
3. RESULTS

3.1. Minor axis cross-sections

From the synthetic images, described in the previous section, we have extracted photometric minor axis cross-sections integrated within one-pixel-wide \((0.0125R_{\text{eff}})\) image strip, passing through the center of the galaxy, for each considered model. The results are presented in Figure 2. Each panel shows surface brightness in \(V\)-band and \(E_{B-V}\) and \(E_{V-K}\) color excess cross-sections determined for “standard” (M5, solid line), “thin” (M6, dotted line), “thick” (M7, dashed line) and “wide” (M8, dash-dotted line) models. Cross-section data are plotted against distance from the model galaxy image major axis, measured in \(R_{\text{eff}}\), for inclination angles of \(0^\circ, 45^\circ, 70^\circ, 80^\circ, 85^\circ\) and \(90^\circ\) (panels arranged in left-to-right direction as indicated in the topmost panel row).

As can be seen in Figure 2, the minor axis cross-sections of the model galaxies clearly show the dusty arms (individual marks of the arms start to merge at a critical angle of about \(70^\circ\)) as well as increasing asymmetry with increasing inclination. \(V\)-band surface brightness cross-sections, presented in top panels of

![Fig. 2. Inclination effect on model galaxy image minor axis cross-sections. Each panel shows surface brightness in \(V\)-band and \(E_{B-V}\) and \(E_{V-K}\) color excess cross-sections determined for “standard”, “thin”, “thick” and “wide” (solid, dotted, dashed and dash-dotted lines, correspondingly) models plotted against distance from the model galaxy image major axis, measured in \(R_{\text{eff}}\). Panels are arranged by inclination in the left-to-right direction as indicated in the topmost panels.](image-url)
Figure 2, show increasing separation between different models with increasing inclination. Similar trends are also observed for $E_{B-V}$ and $E_{V-K}$ color excesses.

Characteristic asymmetries of high inclination (60° to 85°) cross-sections allow one to classify galaxies qualitatively possessing different dust distributions with respect to stellar disk into at least three broad groups. Cross-sections at lower inclinations are less sensitive and more degenerate to the dusty disk parameters and hardly could be applied for the internal extinction distribution analysis in spiral galaxies. The transition between two characteristic inclination angle ranges – low (0° – 70°) and high-inclination (70° – 90°) – is determined by “inter-arm shadowing angle”, which for the model galaxies, analyzed in this study, is approximately 70°. Under this inclination the effective extinction zone (defined as the dusty arm zone with the projected optical depth of $\tau_V > 1$) of the dusty arms significantly shadows the model’s center and the inter-arm regions from direct observation.

3.2. Azimuthally averaged profiles

Azimuthally averaged surface brightness and color excess profiles were computed using a set of elliptical apertures, centered on the geometrical center of the model galaxy with aperture axis ratio, $b/a$, determined from the model inclination angle, $i$, using the following relation

$$\frac{b}{a} = \cos i + \frac{\chi^2 \sin^2 i}{\cos i + \chi \sin i},$$  \hspace{1cm} (3)

where $\chi = Z_{\text{eff}}/R_{\text{eff}}$. Due to the annular arrangement of dusty arms and neglected effects of dust clumpiness in our models the azimuthally averaged profiles computed for model inclination of 90° are less realistic, since the opaque outer dusty arm cuts out the light from the central part of the model too effectively. However, the derived total photometric parameters of the model galaxy are expected to be correct (Semionov & Vansevičius 2002).

Inclination effects on the model galaxy surface brightness and color excess profiles for models with both, a dusty disk and dusty arms (models M5 – M8), are shown in Figure 3. Panels, arranged by the model galaxy inclination angle in the left-to-right direction, as indicated in the topmost row, show $V$-band surface brightness (topmost panel row) and differential $E_{B-V}$ and $E_{V-K}$ color excess (second and third panel rows, respectively) profiles for “standard” (M5, solid line), “thin” (M6, dotted line), “thick” (M7, dashed line), and “wide” (M8, dash-dotted line) models as a function of radial distance given in units of $R_{\text{eff}}$.

As can be seen in Figure 3, in low-inclination (up to ~70°) cases the azimuthally averaged $V$-band surface brightness radial profiles show presence of all three dusty arms for all models, while at the high inclinations only “thin” model profile shows any coherent structure. It is worth noting, that $E_{B-V}$ radial profiles retain information about the number and position of dusty arms up to higher inclinations than $E_{V-K}$ (cf. the relative structure of color excess profiles at inclinations of 45° and 70°). Also a significant flattening of surface brightness profiles at high inclinations (80° and above) is noticeable, while color excess profiles still show the radial gradients comparable or exceeding those observed in low-inclination model galaxies.
Fig. 3. Inclination effects on the model galaxy surface brightness and color excess profiles. Panels show surface brightness in V-band and $E_{B-V}$ and $E_{V-K}$ color excess profiles for “standard”, “thin”, “thick” and “wide” models (solid, dotted, dashed and dash-dotted lines, respectively) measured in rings of increasing radius, given in units of $R_{\text{eff}}$. Panels are arranged by model galaxy inclination in left-to-right direction as indicated in topmost panels.

In order to determine the influence of the dusty arms on photometry performed in elliptical apertures and azimuthally averaged radial profiles we directly compared $E_{B-V}$ color excess and color excess ratio $E_{V-K}/E_{B-V}$ derived from model galaxies possessing only a dusty disk (shown with a solid line) with models having both, a dusty disk and dusty arms (shown with filled circles connected by a solid line). Figures 4 and 5 show $E_{B-V}$ and $E_{V-K}/E_{B-V}$ quantities in growing apertures as a function of aperture major axis, expressed in $R_{\text{eff}}$ units, while Figures 6 and 7 show the differential radial profiles of the respective quantities.

As can be seen in Figure 4, the dependence of the $E_{B-V}$ color excess on the aperture size is determined primarily by the inter-relation of dusty disk scale-height to scale-length ratio, $\chi^d = Z^d_{\text{eff}}/R^d_{\text{eff}}$, with the same parameter of the stellar disk, $\chi$. This results in the “wide” model color excess behaving almost identical to the “thin” model. Furthermore, the difference between models with and without dusty arms depends on the value of $\chi^d$, being negligible for “wide” and “thin” models and strongly increasing for “normal” and “thick” models. This behavior is observed for all inclinations up to nearly edge-on cases (inclination of 85°).

Under the assumption that the dust distribution is generally more concentrated towards the central plane than the star distribution ($\chi^d < \chi$), we conclude that the
Photometric effects of dusty spiral arms

Fig. 4. $E_{B-V}$ color excess measured in a sequence of growing apertures versus radius given in units of $R_{\text{eff}}$. Panels are arranged according to inclination angle ($0^\circ$, $45^\circ$, $70^\circ$, $80^\circ$ and $90^\circ$) and dust-to-star relative distribution (“standard”, “thin”, “thick” and “wide”) in rows and columns, respectively. Solid lines show results obtained for the model galaxies with a dusty disk, solid lines with filled circles show results obtained for the model galaxies with both, a dusty disk and dusty arms.
$E_{B-V}$ color excess value, measured within aperture extending more than $2R_{\text{eff}}$ from the galaxy image center (approximately the distance completely covering the first dusty arm in our model galaxies), is insensitive to the presence of dusty arms (as is commonly assumed on the grounds of small relative cross-section of the dusty arms) for all except edge-on galaxies.

Fig. 5. The same as in Figure 4, but for the color excess ratio $E_{V-K}/E_{B-V}$.
The dependence of the color excess ratio $E_{V-K}/E_{B-V}$ on aperture size, shown in Figure 5, however, is significantly more complicated. In low-inclination cases (up to 70°) for the apertures, covering more than half of the total model galaxy radius ($>3R_{\text{eff}}$), the introduction of dusty arms (and thus an increase in total extinction and, therefore, in expected dust mass) leads to the increase in $E_{V-K}/E_{B-V}$. The dependence of the color excess ratio on aperture size beyond $3R_{\text{eff}}$ for models with and without dusty arms is very similar, thus it might be possible that the introduction of dusty arms affects $E_{V-K}/E_{B-V}$ in a manner identical or similar to an increase of the dusty disk's total extinction. However, this statement requires further investigation. It should also be noted, that color excess ratio $E_{V-K}/E_{B-V}$, measured within small apertures ($\sim R_{\text{eff}}$ or less) does not provide a good estimate of color excess ratio for the entire model galaxy and is strongly dependent on dust distribution geometry, particularly for high-inclination cases.

Significant is the fact, that in the case of aperture photometry for low-inclination models (inclination of up to 50°, Figures 4 and 5) the respective values remain nearly constant for the large extent of the profile, thus allowing the determination of total dust content and scale-length of dusty disk using aperture photometry.

Radial profiles of $E_{B-V}$ color excess and color excess ratio $E_{V-K}/E_{B-V}$ (Figures 6 and 7, respectively), derived from azimuthally averaged surface brightness profiles, show that for all models, seen under low inclination (below 70°), dusty arm effects are well localized. The central, outer and inter-arm region profiles of the model galaxies with both, a dusty disk and dusty arms, are very similar to the profiles computed for the models with a dusty disk only. The presence of the dusty arms is clearly seen in all radial color excess profiles of low-inclination models and their number and position (radial distance) can be easily determined. For higher inclination models (80°–90°) the radial color excess profiles show no significant effect due to presence of dusty arms as the individual dusty arm profiles become overlapped and indistinguishable.

The photometric effect of the dusty arms significantly depends on optical density (opacity) difference between the dusty arms and the dusty disk (“arm contrast”). The dusty arms are the least prominent in the “wide” model and the most prominent in the “thick” model. As is obvious from geometric considerations, the “thick” model color excess profile also displays the prominent effects of overlapping dusty arms under lower inclinations than other models, the effect already being significant at 70° inclination.

Color excess ratio $E_{V-K}/E_{B-V}$ profiles (Figure 7) behave similarly to the above discussed $E_{B-V}$ color excess profiles, additionally showing presence of dusty arm-scattered light in the outermost parts of the models under low inclinations. However, in this case the most prominent effects of dusty arms are seen in the “thin” model profiles.

### 3.3. Effective model galaxy extinction and color excesses

In the following we discuss the inclination dependence of the total extinction in $V$-band, $A_V$ and $A_V/E_{B-V}$ as well as $A_V/E_{V-K}$ ratios. The effect of multiple photon scattering from the dusty arms can be tested using the innermost part of the model, enclosed within the first dusty arm, particularly when seen under low inclination, while the direct shadowing of the model central region by the dusty arms is negligible. Furthermore, due to selection effects, only the brightest parts of the distant galaxies are usually observable.
Fig. 6. $E_{B-V}$ color excess measured in a sequence of elliptical annuli. Panels are arranged according to inclination angle (0°, 45°, 70°, 80° and 90°) and dust-to-star relative distribution (“standard”, “thin”, “thick” and “wide”) in rows and columns, respectively. Solid lines show results obtained for the model galaxies with a dusty disk, solid lines with filled circles show results obtained for the model galaxies with both, a dusty disk and dusty arms.
Fig. 7. The same as in Figure 6, but for the color excess ratio $E_{V-K}/E_{B-V}$.

Therefore, we present two sets of results: the photometry parameters obtained for aperture with semi-major axis radius of $1R_{\text{eff}}$ (the central model galaxy region fully enclosed within the innermost dusty arm) and for aperture with semi-major axis radius of $6R_{\text{eff}}$ (the entire model galaxy).

As can be seen in the upper row of Figure 8, in most low inclination (up to $60^\circ$) cases the presence of dusty arms has no significant impact on the extinction in
V-band in the central part of the model galaxy. The effect of the innermost dusty arm shadowing the central part of the model galaxy is determined by the scale-height of the dusty disk, increasing from the “thin” through the “standard” to the “thick” model cases. Again, the “wide” model extinction behaves similarly to the “thin” model having the same $\chi_d$ value. This leads to the conclusion that the effect of light back-scattering by dusty arms can be neglected, while in the cases of dust distribution extending above the stellar populations the “shadowing” effect becomes significant.

![Graph](image)

**Fig. 8.** The extinction in V-band, $A_V$, vs. model galaxy inclination angle. Top row panels show $A_V$ measured in aperture with semi-major radius of $1R_{\text{eff}}$; bottom row panels show total extinction in aperture with semi-major radius of $6R_{\text{eff}}$ (entire model galaxy). Panels are arranged in columns according to relative dust-to-star distribution (left-to-right): “standard”, “thin”, “thick” and “wide”. Solid lines with filled and open circles correspond to the models with and without dusty arms, respectively.

When considering the extinction of the entire model galaxy (Figure 8, bottom panels) it is noticeable that the presence of dusty arms increases the extinction by a constant value, weakly dependent on the scale-height of the dusty disk. This behavior is identical for all models with inclinations between $0^\circ$ and $70^\circ$. The edge-on extinction, however, is strongly dependent on the vertical extent of the dusty arms. This can be interpreted as dusty arms being almost a perfect “screen”, with scattering due to their presence, apparently playing only a minor role in the final photometry results. The high-inclination models exhibit strong increase in the extinction due to shadowing by the dusty arms, strongly dependent on the $R_{\text{eff}}$. 
Fig. 9. The same as in Figure 8, but for the $A_V/E_{B-V}$ ratio.

Fig. 10. The same as in Figure 8, but for the $A_V/E_{V-K}$ ratio.
The effects of the dusty arm presence on extinction to color excess ratios $A_V/E_{B-V}$ and $A_V/E_{V-K}$ within aperture of $1R_{eff}$ semi-major axis radius, shown in the upper row panels in Figures 9 and 10, respectively, are noticeable only for the “thick” models seen under inclinations of $80^\circ$ and higher. This provides a direct, although inclination-dependent, relation between color excess and extinction for the central part of the model galaxy, which is apparently independent of the surrounding dusty arm presence.

Extinction to color excess ratios $A_V/E_{B-V}$ and $A_V/E_{V-K}$ determined for the entire model galaxy (bottom row panels of Figures 9 and 10, respectively) show nearly constant increase for model galaxies with dusty arms in respect to the models with a dusty disk only. This difference weakly depends on the scale-height of the dusty disk and remains nearly constant up to the inclination of $70^\circ$ – for higher inclinations it increases sharply. This behavior can be attributed to the increase in total dust mass of the model galaxy, and it shows almost no effect of the dusty disk for the low inclination models.

Inclination dependencies of color excess ratio $E_{V-K}/E_{B-V}$ (Figure 11) show no effect of dusty arm presence on the photometry of the model galaxy central part, and moderate inclination and scale-height dependent effects for the entire model galaxy, following the trends similar to $A_V/E_{B-V}$ ratio discussed above. Therefore, $E_{B-V}$ and $E_{V-K}$ color excesses seem to be very good measures of total internal extinction in disk galaxies independent of dusty arm presence.

![Figure 11](image-url)

**Fig. 11.** The same as in Figure 8, but for the $E_{V-K}/E_{B-V}$ ratio.

We find no significant differences between $E_{B-V}$ and $E_{V-K}$ color excesses of the model galaxies, having only a dusty disk and the equivalent models with both, a dusty disk and dusty arms, possessing smaller flatness of dust distribution than...
flatness of stellar population, $\chi > \chi^d$ (the “thin” and the “wide” models), versus the inclination of up to 70°. At the same time, the “standard” and the “thick” models show significantly differing behavior of $E_{B-V}$ and $E_{V-K}$ color excesses versus inclination arising due to dusty arms.

4. DISCUSSION AND CONCLUSIONS

As it was demonstrated by the simplified models in section 3, dusty arms may significantly affect the surface brightness dependence on the inclination of disk galaxies, when the dust lanes, tightly coupled with spiral arms, are prominent and their absorbing material extends above the stellar disk. On the contrary, when the dust lanes are marginal and flattened to the central plane of the galaxy disk, their extinction effects can be ignored as is assumed in the conventional models (see e.g., Misiriotis et al. 2000).

The geometric proportions of studied model galaxies are inherent to the real galaxy properties, see e.g., Kodaira, Watanabe & Okamura (1986). The pitch angle of the spiral arms is small in the early-type disk galaxies and increases as spiral arms become loose and irregular with increasing morphological type index. Therefore, the “standard” and the “thin” dusty arm models (M5 and M6) may roughly approximate the spiral galaxies of Sa-Sc ($T = 1–5$) types. As the disk galaxies of early types have a prominent bulge, which responds differently to the extinction produced by the absorbing matter residing with the disk (Kodaira et al. 1992), the shadowing effects discussed in this paper are most relevant to the disk galaxies of the middle morphological types Sb-Sc ($T = 3–5$). The special example of the Sombrero galaxy (NGC 4594, Sa, $T = 1$) clearly shows an obscuring dusty ring at the outermost part of the stellar disk, see e.g., Ohta & Kodaira (1995). Although, normal Sb-Sc galaxies do not show this kind of structure, the contrast of spiral arms to the smooth stellar component in the disk becomes stronger outwards, therefore, that also suggests the relevance of the models, presented in this study, to the main part of normal Sb-Sc galaxies.

While it is tempting to compare the results, obtained for the “thick” model to the “boiling disk” hypothesis proposed by Sofue et al. (1994), it should be done with caution. First, the extinction distribution in observed cases show a considerable amount of filamentary structure, which is hard or nearly impossible to model using smooth extinction distribution. Second, as argued by Davies et al. (1998), the blown-up dust comes from the immediate vicinity of the star-burst regions, therefore increasing the vertical thickness of the dusty arms. Whether this mechanism also increases the thickness of the dusty disk remains uncertain. The “thick” model was included in this study to illustrate the extreme case opposite to the “thin” model and represent the closest model to the classical “screen” extinction approximation.

The performed tests show that determination of the dusty disk geometry is crucial in reconstructing the properties of global radiation field in disk galaxies. The fact, that the increase in the total dust mass of the model galaxy (due to introduction of dusty arms) by over 200% has such a small effect on the photometric properties, leads to a conclusion that it might be possible to model successfully photometric galaxy parameters using stellar disks homogeneously coupled with the dusty disks, thus supporting the current trend of ignoring the effects of spiral arm presence and using smoothed double-exponential and similar distributions. At the same time, this may have a profound implication on the efforts to determine
the effective extinction using metallicity as a single parameter of the interstellar matter mass, obtained from observations or from evolutionary models (see e.g., Vansevičius, Arimoto & Kodaira 1997). The results presented in this work show, that an increase in total dust mass by a factor of 3 may change the resulting $A_V$ extinction value by 20–100\% (even barring the extremes, seen in our models under the inclination of $\sim 90^\circ$). Therefore, in order to estimate the effective galaxy extinction, basing on metallicity of interstellar matter, it might be necessary to introduce a parameter reflecting the morphology of a given galaxy in addition to the dust clumpiness parameter suggested by Nagashima et al. (2002).

Both, theoretical considerations and radiative transfer models, suggest the presence of two clearly separable effects of dusty arms: direct light “shadowing” and light “localization” in the regions between dust walls. The latter effect is more prominent and is seen in all considered cases. Color excesses provide a good measure of total internal extinction for all model galaxies regardless of dusty arm presence. Furthermore, the results obtained with growing apertures show that photometric properties of the model galaxies derived with large apertures “sense” additional extinction produced by dusty arms. However, the effect is much weaker than it would be in the case of the same dust mass diffusely distributed in the dusty disk rather than in the arms. On the other hand, the photometry of the central part alone is insensitive to the presence of surrounding dusty arms up to very high inclination angles. This may affect the conclusions drawn basing on observations of only the central parts of distant galaxies and must be investigated further.

The above considerations lead to the conclusion that dark lanes are substantial contributors to the extinction effects of disk galaxies of morphological types Sb-Sc. We suggest that the dusty spiral arm component should be taken into account in studies of spiral galaxy extinction, in addition to the conventional diffuse dust layers or disks. However, in order to make the model galaxy study more realistic, well adjusted specific information about the optical thickness and the geometric parameters of spiral dark lanes, dependent on galaxy type, must be introduced. In future works dust clumpiness and thermal emission effects should also be fully addressed in order to make detailed comparison of the model spiral galaxy photometric properties with observations.

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