Bogus dust screens from well-mixed exponential discs in galaxies

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ABSTRACT
The V – K colours along the minor axes of spiral galaxies typically change from red to blue with increasing distance, giving the impression that the near side is systematically screened by dust. Such a preferred orientation for dust screens is unlikely. Here we show that common extinction from the embedded dust layer in an exponential disc has the same effect, making the near side systematically redder as the inclination increases. The galaxy NGC 2841 is modelled as an example, where the V – K profile is profoundly asymmetric and actually step-like across the centre. We predict that the minor-axis emission profile of the same dust in the far-infrared, at wavelength λ ~ 200 μm, will be much more symmetric than the optical profiles, implying nearly equal column densities of dust on both sides of the minor axis.

Key words: dust, extinction – galaxies: fundamental parameters – galaxies: individual: NGC 2841 – galaxies: ISM – galaxies: spiral – infrared: galaxies.

1 INTRODUCTION
The recent development of K’-band (2.1-μm) and K-band (2.2-μm) imagery for nearby galaxy discs led to the unexpected discovery of large V – K’ and V – K colour gradients along the minor axes when the inclinations exceed ~60°. The ‘Evil Eye’ galaxy NGC 4826 exhibits a sudden increase by ~1 mag from V – K = 4 mag to V – K = 5 mag in the dust-attenuated ‘screen’ (Block et al. 1994a). Similarly large V – K jumps occur in other highly inclined spirals, such as NGC 3521 (Panel 188 in Sandage & Bedke 1994). Explanations for this effect vary from an intervening dust screen (Witt et al. 1994) to high-latitude scattering from dust (Block, Elmegreen & Wainscoat 1996). The problem with the screen model is that the apparent dust is always on the near side of the galaxy, even though we expect random orientations for galaxies in space. The problem with the high-latitude dust model is that there is no ubiquitous evidence for such dust, although extraplanar dust in specific examples has been detected (e.g. Howk & Savage 1997).

This paper shows how absorption and scattering at V and K bands by dust embedded in an exponential disc can produce observable colour gradients which may be remarkably asymmetric or even step-like. The reason is that the near side of an exponential disc is brighter at smaller radius behind the dust in the mid-plane, while the far side is brighter at smaller radius in front of the dust in the mid-plane. Thus the near side has a higher fraction of the same total light blocked by dust.

Other models have considered similar effects. Kodaira & Ohta (1994) and Ohta & Kodaira (1995) measured and modelled V- and J-band differential extinction profiles [≡ − ln(I_dif/I_near)] along the minor axes in several galaxies, without including scattered light; they did not discuss colour gradients specifically, although the existence of such gradients can be inferred from their analyses. Byun, Freeman & Kylafis (1994) considered B- and I-band minor-axis profiles with scattering included, but also did not specifically address the resulting near–far colour differentials (although again they can be inferred from their separate B and I profiles). Kuchinski & Terndrup (1996) plotted J – K colour profiles along the minor axes of several galaxies, but discussed and modelled only the spherical bulge systems, including scattered light. Here we determine the line-of-sight V – K colour gradient in disc + bulge galaxies using radiative transfer with direct and single-scattered light.

2 MODELS
Stellar and gaseous discs are modelled with exponential brightness and density profiles in both the radial and perpendicular directions, following the work of others referenced above. For the stellar volume emissivity, we use

\[ j(r, z) = \exp\left(-r - \frac{|z|}{z_D}\right) + \frac{\kappa_\text{St}}{(1 + R^2/R_b^2)^{1.5}} \]

(1)

and for the dust extinction (scattering + absorption),

\[ \kappa_\lambda(r, z) = \kappa_\lambda(0, 0) \exp\left(-r - \frac{|z|}{z_g}\right) + \frac{\kappa_\text{St}(0, 0)}{(1 + R^2/R_b^2)^{1.5}} \]

(2)

All distances are normalized to the disc scalelength; r is the distance to a point measured parallel to the disc, and R is the total galactocentric distance, in three dimensions. The volume emissivity is normalized to unity for each wavelength, because we are concerned primarily with differential (near–far side) colour gradients. The intrinsic stellar colours do not matter as long as they are the same at
each radius on the near and far side of the disc. Radial colour gradients in the disc do not matter for a near–far comparison either.

The equation of radiative transfer gives the intensity $I$ measured by an observer outside the galaxy at wavelength $\lambda$:

$$I_b(\lambda) = \int_0^{\pi} \int_0^1 df(\xi) \int_0^{2\pi} d\phi \cos \phi (\delta \xi)^2 \left[ \xi_0 \kappa_0 (r, z) \exp \left( - \int_0^r \kappa_0 (\tilde{r}, \tilde{z}) d\tilde{r} \right) \right] \exp \left( - \int_0^l \kappa_1 (r, z) d\xi \right) \right]. \quad (3)$$

The distance along the line of sight is $\xi$, increasing away from the observer; $\xi_0$ and $\xi_1$ are the near and far limits of the integral through the galaxy, taken here to be the hypotenuse of a triangle with a maximum total in-plane radial extent of 5 scalelengths and a maximum total half-thickness of 3 scalelengths. The argument of $I_b, \iota$ is the galaxy inclination.

The volume emissivity from single scattering is

$$j_{\text{scat}}(r, z) = \kappa_0 (r, z) A_0 \int_0^\pi df(l) \int_0^{2\pi} db \cos b \phi(\theta) \cos \theta = \frac{1}{4\pi} \frac{1 - g^2}{1 + g^2 - 2g \cos \theta}^{1/5},$$

where $\xi_2$ is the maximum distance along a path through the galaxy, and $l$ and $b$ are the galactic longitude and latitude as seen by an observer at point $x$ in the integral for $I_b$. $\phi$ is the scattering phase function (Henyey & Greenstein 1941),

$$\phi(\theta) = \frac{1}{4\pi} \frac{1 - g^2}{1 + g^2 - 2g \cos \theta}^{1/5}, \quad (5)$$

and $\theta$ is the scattering angle, given by

$$\cos \theta = -\sin b \cos i + \cos b \sin i \cos l. \quad (6)$$

In equation (4), $A_0$ is the albedo at wavelength $\lambda$. While most interstellar grains were thought to be substantially smaller than near-infrared wavelengths (Mathis, Rumpl & Nordsieck 1977), the upper size limit of dust grains — to which the near-infrared albedo is extremely sensitive — has been revised (see Kim, Martin & Hendry 1994). The first extragalactic determination of the near-infrared dust albedo was made by Witt et al. (1994), who concluded that the albedo of dust grains at $V$ and $K$ may be identical. This high near-infrared albedo was alluded to by a number of diverse observations (Lehtinen & Mattila 1996 for the Thumbprint Nebula; Block 1996 for the Whirlpool Galaxy M51 and its companion; Pendleton, Tielens & Werner 1990 and Sellgren, Werner & Dinerstein 1983 for infrared and classical reflection nebulae). We choose values for the optical and near-infrared albedos of dust grains to both be $A = 0.6$ in the $V$ and $K$ passbands.

Furthermore, dust grains are predominantly forward scattering in the optical (e.g. Whittet 1992), while near-infrared values of $g$ at $K$ lie between 0.1 and 0.6 (Witt et al. 1996). We choose $g = 0.5$ in $V$ and $K$. There is only a weak dependence on $g$ as far as albedo determinations are concerned (fig 2 in Witt et al. 1996), and our models with different values of $A$ did not change much; lower $A$ gave about the same results as slightly higher extinctions, approaching the results with no scattering, as shown in the figures by dashed lines.

The intensity $I_b$ was determined from these equations as a function of distance from the galactic centre for various galaxy inclinations. For each distance and inclination, the reddening difference between the near and far sides of the disc was evaluated in magnitudes:

$$E(V - K)_{\text{near}} - E(V - K)_{\text{far}} = -2.5 \log_{10} \left( \frac{I_b}{I_L} \right)_{\text{near}} + 2.5 \log_{10} \left( \frac{I_b}{I_L} \right)_{\text{far}}. \quad (7)$$

For most of the models shown here, the perpendicular scale-heights are taken to be $z_c = 0.1$ and $z_e = 0.2$, and the bulge scalelength is $R_b = 0.1$ (Kodaira & Ohta 1994). The relative volume emissivity of the bulge is $e_b \sim 0.5 (L_b/L_d) z_c / R_b^2$ (Kodaira & Ohta 1994). The ratio of bulge to disc luminosity is $L_b / L_d = 0.1$ at the $K$ band (Byun, Freeman & Kylafis 1994) and $0.1 \times 10^{-3.4\Delta M}$ at the $V$ band for a colour difference $\Delta M = 0.5$ mag between the bulge and the disc. The central extinctions for the disc are taken to be $K_{V,J}(0,0) = 10$ or 15 optical depths (o.d.) kpc$^{-1}$ for the models shown by the figures, and for the bulge are $K_{V,J}(0,0) = 0$, or 10 o.d. kpc$^{-1}$ (1 optical depth $= \log 0.4 = 1.087$ mag). In all cases, $\kappa_K = 0.1 \kappa_V$. The value of $K_{V,J}(0,0) = 10$ o.d. kpc$^{-1}$ might be appropriate for the Milky Way: it gives a $V$-band extinction of 1.47 mag kpc$^{-1}$ at $r = 2$ disc scalelengths, which is about the extinction at the solar radius. Many other values for these quantities were modelled too, and some of the results will be discussed for comparison.

Fig. 1 (top) shows the colour excess versus distance along the minor axis for a model with a central disc extinction of 10 o.d. kpc$^{-1}$ in $V$ and no additional extinction in the bulge. The projected distance along the minor axis, $x \cos i$, is on the abscissa, in units of the intrinsic disc scalelength; negative values of this distance represent the near side of the galaxy. Both the bulge and disc emissions are included here, but there is no bulge extinction in this model. Cases with scattered light are shown by solid lines, and cases without scattered light are shown by dashed lines. Inclinations of $50^\circ$, $60^\circ$, $70^\circ$ and $80^\circ$ are plotted; the near-side reddening increases...
with inclination. Any intrinsic disc colour gradient that might be present in the stars is ignored.

The $V-K$ colour differences between the near and the far sides are shown in the bottom panel of Fig. 1. There is a maximum in differential reddening at about 0.2 disc scalelength, where the visual extinction is $\sim 8$ o.d. kpc$^{-1}$. Intrinsic disc colour gradients would not matter for this diagram, as long as the near and far sides of the disc have the same intrinsic colours at the same radii.

Fig. 2 shows the same model as Fig. 1, but with extinction in the bulge. For the assumed central bulge extinction of $K_{V, B}(0, 0) = 10$ o.d. kpc$^{-1}$, the extinction at a radius of 1 disc scalelength is $10 \times (1 + (1/0.1)^2)^{-1/2} = 0.01$ mag kpc$^{-1}$, which is much smaller than the disc extinction at this radius. Nevertheless, dust in the bulge clearly reddens the far side of the V-K colour profile, making the $V-K$ colour difference at the bottom of the figure about a factor of 2 less than in Fig. 1.

Fig. 3 shows the observed $V-K$ scan along the minor axis of the inclined flocculent galaxy NGC 2841 (studied in more detail by Block et al. 1996). The strong colour gradient between the near (left in the figure) and far sides is evident, as discussed in our previous paper. The models in Figs 1 and 2 do not reproduce this gradient well, because NGC 2841 has a central hole in molecular gas inside 1 disc scalelength (Young & Scoville 1982), and it has a low H$\alpha$ column density there too. Thus there is probably a dust hole inside 1 scalelength. This hole was also evident in a scan of $V-K$ colour versus distance along the major axis of NGC 2841 (Block et al. 1996), which shows a dip toward bluer colour inside 1 disc scalelength. This blueness approaches the true colour of the inner disc, without extinction. In addition to the dust hole, NGC 2841 also has a relatively high extinction perpendicular to the disc compared to the Milky Way (Block et al. 1996), so we need to consider slightly larger $\kappa$ than in the previous figures.

Fig. 4 shows the minor-axis profile from a model with 1.5 times the extinction as in Fig. 1, but with a central hole made by setting the dust density profile equal to $e^{-r}$ instead of $e^{-\kappa r}$ for radius $r$, measured in units of the scalelength. This function gives a peak in the gas density at $r = 1$, with a hole inside this and a nearly exponential disc beyond. The model has the same four inclination
angles as in the previous plots, for general use in other studies; the inclination of NGC 2841 is $68^\circ$, which is essentially the same as for the third curve up from the bottom (which is for $70^\circ$). With a hole in the model and no dust in the bulge, the fit to the data is good, i.e., the near side is redder than the far side by $0.4$ mag, and the far side colour excess distribution is relatively flat. The small-scale variations in the data for NGC 2841 are presumably from dust lanes, which are not part of the present model (but see Block et al. 1996 for radiative transfer fits to these dust lanes).

Fig. 5 shows the same disc-hole model as in Fig. 4, but with extinction in the bulge as in Fig. 2. This model does not fit the data for NGC 2841, because the far side is too red with the additional extinction from the bulge, giving the far-side part of the curve on the top of Fig. 5 a downward slope, unlike the observations of NGC 2841 and the corresponding curve in Fig. 4, where this far-side $E(V - K)$ scan is flat. The dusty-bulge model also has an increased reddening in the central region, which becomes even more prominent for face-on orientations. Any larger $K_{V, B}(0, 0)$ makes this central reddening unacceptably large even for the inclination of NGC 2841. Thus the upper limit to the amount of bulge dust in NGC 2841 is about the value in Fig. 5, which corresponds to less than $0.01$ o.d. kpc$^{-1}$ at one scalelength, or an equivalent hydrogen density of $< 0.007$ cm$^{-3}$, using the standard conversion of dust to gas (Bohlin, Savage & Drake 1978). Evidently our previous suggestion (Block et al. 1996) that the near–far colour difference in NGC 2841 is the result of bulge scattering by dust high off the plane is not correct.

The variable geometry of dust and starlight along the line of sight makes the relationship between colour excess and extinction non-linear, unlike the common interstellar case where an absorbing cloud is in front of a single star. Fig. 6 plots the reddening versus the optical depth through the disc for the Milky Way and NGC 2841 models with no bulge dust (from Figs 1 and 4) and with scattered light included. The projected radius along the minor axis varies along each curve, from the near side of the disc (solid line) to the far side (dashed line). The same four inclination angles are shown. The relationship between reddening and extinction is double-valued, because the near side has more reddening per unit dust column density than the far side.

3 DISCUSSION

Differential reddening between the near and far sides of a galaxy disc may be understood as follows. The radial light gradients in the bulge and disc cause the near side to have a brighter light source behind most of the disc dust, while the same gradients on the far side cause it to have its brighter light source in front of the disc dust. Thus the disc dust has more light to block on the near side than the far side. Consequently, the near side is dimmer (Byun, Freeman & Kylafis 1994; Kodaira & Ohta 1994) and significantly redder. Models with the same scaleheight for the dust and stars (not shown) have even stronger colour differentials because more of the starlight is extinguished. Models with more disc extinction also have more differential reddening, and models with dust in the bulge have less because the bulge dust makes the far side redder.

Minor-axis colour gradients are present in many of the galaxies in Wray’s Color Atlas (1988) and are even more prominent in $V - K$ images of inclined galaxies (see, e.g., Block et al. 1994a, Thornley 1996, 1997, Peletier & Balcells 1997 and Grosbøl & Patsis 1998).
Thornley (1996) found that in NGC 5055, optical depths suddenly jump from 0.5 on the far side to 4–5 on the near side.

The models presented here show that such colour gradients are a natural result of extinction from well-mixed dust embedded in the disc, and it is predicted that for large enough inclinations, particularly in galaxies with inner-disc dust holes, the near–far asymmetry in \( V - K \) profiles may even be step-like. Near-side dust screens are not needed, even for the dramatic jump of \( E(V - K) \sim 1 \) mag in NGC 4826. There is some sensitivity of the colour gradient to the precise distribution of dust, such as the presence or lack of a central hole, and this may be useful in modelling discs.

Another point to stress is that the far side, although bluer, cannot be considered *dust-free* or unobscured – terms that continue to be used in the literature. For example, the Andromeda spiral M31 shows prominent dust lanes on the far side as well as the near side in both the *IRAS* 60- and 100-\( \mu \)m maps (e.g. Habing et al. 1984; Walterbos & Schwering 1987). NGC 2841 also has arms of dust in a dust-free hole, and this may be useful in modelling discs.

In infrared space observatory, amounts of cold dust, which accounts for anoptical depth, the far-infrared emission profile of NGC 134, shown in Fig. 7, is in fact almost perfectly symmetric. The far-infrared emission profile of M51 at 15 m (Alton et al. 1998) by the *IRAS* 60- and 100-\( \mu \)m maps (e.g. Habing et al. 1984; Block et al. 1994a; Block 1996), reside on either side of the galaxy can be determined from the colour gradient if trailing spiral arms are present. Such determinations may be useful for crowded fields of distant galaxies in an attempt to look for alignment or other attributes of spin orientations without the tedious job of taking slit spectra to get rotation curves. This characteristic of disc colour might also be useful in searching for leading spiral arms in galaxies with rotation curves. Such arms apparently occur in some accreting galaxies (NGC 4622: Buta, Crocker & Byrd 1992, see also fig. 7 in Block et al. 1994b and plate 4 in Bertin & Lin 1996; NGC 4826: van Driel & Buta 1993).

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Figure 7. Surface brightness along the minor axis of the galaxy NGC 134 at 200 \( \mu \)m, from Alton et al. (1998), showing symmetry in cold dust emission even though this same dust presents a striking asymmetry with foreground ‘screening’ in optical images.
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