Astron. Astrophys. 338, 795–806 (1998)

ASTRONOMY AND ASTROPHYSICS

Near-infrared observations of galaxies in Pisces-Perseus

II. Extinction effects and disk opacity

G. Moriondo[1,2], **R. Giovanelli**[2], **and M.P. Haynes**[2]

[1] Dipartimento di Astronomia e Scienza dello spazio, Universita' di Firenze, L. E. Fermi 5, I-50125 Firenze, Italy
[2] Center for Radiophysics and Space Research, Cornell University, Ithaca, NY 14853, USA

Received 28 April 1998 / Accepted 28 May 1998

Abstract. We study the correlations with inclination of H-band disk and bulge structural parameters and $I-H$ colour profiles for a sample of 154 spiral galaxies, in order to detect possible effects due to internal extinction by dust. The selection of the sample assures that galaxies at different inclinations are not intrinsically different, so that the observed correlations represent the real behaviour of the parameter considered. All the parameters are derived from a bi-dimensional fitting of the galaxy image. We find that extinction, though small at near infrared wavelengths, is sufficient to produce observable effects. In particular the observed increase of the average disk scalelength and the reddening of the disk $I-H$ colour at high inclinations are clear signatures of the presence of dust. The total H-band disk luminosity depends little on inclination; on the other hand significant corrections to the face-on aspect are derived for the H-band central disk brightness and the disk scalelength. The bulge parameters exhibit little or no dependence on inclination. Simulations carried out with a simple model for an internally-extincted galaxy show that these results imply a central H-band optical depth between 0.3 and 0.5.

Key words: galaxies: photometry – structure – ISM – infrared: galaxies

1. Introduction

The amount of internal extinction in spiral disks has been the subject of a long series of papers throughout the last few years, since Disney et al. (1989, DDP hereafter) and Valentijn (1990), questioning the widespread assumption of transparency of galaxies, suggested that disks might actually be optically thicker than previously thought. In particular their claim was in disagreement with the conclusions by Holmberg dating back to 1958 and 1975. Subsequent papers (e.g. Peletier & Willner 1992; Jansen et al. 1994; Giovanelli et. al 1994 – G94 hereafter) tend to support a scenario in which galaxies are transparent in the outer regions and moderately opaque at the center. Though this is likely to be the case, the actual amount of extinction in spiral disks is still a matter of debate. On the other hand, estimating the internal extinction in disks and how it affects the observed light distribution is necessary in order to correct the observed quantities to either the face-on aspect or the dust-free case. Such corrections are fundamental in any study concerning galaxies both as single objects (structure and evolution), and as tracers of the large scale structure of the universe.

A possible approach to characterizing the extinction properties of disks relies on the statistical properties of large samples of galaxies, for example, analyzing the correlations of observable parameters with inclination. In this way, average corrections to the face-on aspect for such quantities can be calculated in principle without introducing any modeling of the extinction processes. On the other hand, simulations of extincted galaxies (e.g. Byun et al. 1994; Bianchi et al. 1996; Corradi et al. 1996) can predict the trends observed, and therefore provide insights into the parameters of the dust layer, such as the thickness or the central optical depth $\tau(0)$. A few caveats need to be considered when undertaking a study of this kind. First of all, simulations have shown that some tests are not significant at any optical depth, since in some cases a large variation in $\tau(0)$ has only a minor influence on a particular parameter. Using many different correlations at the same time will necessarily yield a more confident estimate of the opacity. Of course every structural parameter (scalelength, surface brightness, the inclination itself) needs to be determined in a most reliable and objective way, possibly separating the two contributions from bulge and disk to the total brightness distribution. If simulations are used to predict the observed trends with inclination, a comparison is possible only if real and simulated data are analyzed in a similar way. In fact different decomposition techniques often yield discrepant estimates of the measured parameters as pointed out, e.g., by Knapen & van der Kruit (1992). Finally, in the galaxy sample used for the analysis, possible observational biases need to be accounted for, as demonstrated by several authors (Burstein et al. 1991; Davies et al. 1993; Giovanelli et al. 1995 – G95 hereafter). Davies et al., for example, showed that galaxies from a diameter-limited sample tend to be characterized by a preferred value of the central disk surface brightness $\mu(0)$, which is determined by the visibility function of that sample (Davies 1990). This preferred value does not depend on the inclination or on

Send offprint requests to: G. Moriondo the intrinsic distribution of surface brightness, so that any conclusion about the disk opacity derived by simply investigating the observed correlation of $\mu(0)$ with inclination is in general affected by this selection effect.

In this paper, we study how the bulge and disk structural parameters correlate with inclination in the near infrared (NIR), in order to detect and quantify the effect of internal extinction at these wavelengths. To this purpose we use a sample of 154 spiral galaxies in the Pisces-Perseus supercluster region, for which H band images are available. These data were collected for a project aimed to investigate the structural, photometric and dynamic properties in the NIR of a large homogeneous sample of spirals, for which a reliable estimate of the amplitude of internal extinction is necessary. This study can also provide information on the general issue of disk opacity, beyond its NIR perspective. In fact, if disks are optically thick in the B band, we expect them to be only partly opaque in the NIR, and simulations clearly show that some of the correlations with inclination (in particular the correlations of central brightness and scalelength) are useful and significant only in the case of *moderate* opacity.

The separation of the bulge and disk contributions to the total light, and the subsequent determination of the various structural parameters of the two components, is carried out using the entire galaxy image, instead of a brightness profile, which considerably improves the reliability of the results (Byun & Freeman 1995; Moriondo et al. 1998). Since the sample is selected from a single supercluster the scatter introduced by distance selection biases are minimized. For about 70 galaxies of the sample I band brightness profiles are also available, from the ScI sample of Haynes et al. (in preparation). for these objects $I-H$ colour profiles were also used to investigate the extinction properties of the disks.

We first describe the data analysis and discuss the correlations between the various parameters and the inclination, summarizing briefly the trends expected at different opacity levels. Next we account for possible selection effects on the sample and define an intrinsically homogeneous set of galaxies. We finally discuss the trends observed in our sample and we compare our results with the predictions of a model for an extincted galaxy, deriving an estimate for the central optical depth in the H band. Throughout the paper we assume a Hubble constant $H_0 = 75$ km s^{-1} Mpc^{-1}.

2. The sample

Our galaxies belong to a sample selected in the region of the Pisces-Perseus supercluster and were initially drawn from the target of the redshift survey of this region carried out by R.G. and M.H. Selection criteria, observations, data reduction and photometric calibration are described in Moriondo et al. (in preparation). One hundred seventy seven galaxies were imaged in the NIR photometric bands (J, H, and K), with types ranging from S0 to Sd and covering the whole range of inclinations – though with fewer objects at high inclination. Since for a large fraction of these objects only H band data are available, in the remainder of the paper we will consider only the H band subsample (173 galaxies as a whole, mostly late-type spirals).

Distances were evaluated correcting the heliocentric radial velocities to the CMB frame of reference with the prescription reported in RC3 (de Vaucouleurs et al. 1991). The average distance of the sample is 70 Mpc with a dispersion of 24, yielding an average H-band absolute magnitude of -23.4; the luminosity range is between ~ -21 and ~ -25 H-mag.

3. Data analysis

A surface brightness profile was extracted for each galaxy using the ELLIPSE routine in the STSDAS[1] package for data reduction and analysis. In particular, the ellipse fitting was performed keeping the center of the ellipses fixed, but allowing ellipticity and position angle to vary. From such profiles we determined the isophotal radii considered in the following analysis. They were also used to obtain $I-H$ colour profiles, as described in Sect. 6.5.

To obtain a description as reliable and objective as possible of the galaxy structure, rather than merely determining the outer slope of the major axis profiles, we fitted a bi-dimensional model brightness distribution convolved with a gaussian PSF to each galaxy image. The model includes two components, a disk and a bulge, whose apparent brightness distributions are both elliptical and decrease exponentially with radius. In a magnitude scale, along the major axis:

$$\mu(r) = \mu(0) + 1.086\frac{r}{r_d} \quad . \tag{1}$$

We expect an exponential shape for the bulge to be appropriate for these galaxies since almost all of them are Sb's or later types (see for example Andredakis et al. 1995), and in fact this choice is supported a posteriori by the good quality achieved by most of the fits. When the exponential distribution for the bulge is too steep to yield a satisfactory fit to the data (7 cases out of 174) we consider a generalized distribution for this component (Sèrsic 1968), i.e.:

$$\mu_b\,(r) \;= \mu_e + 1.086 \left\{ -\alpha_n \left[\left(\frac{r}{r_e} \right)^{1/n} - 1 \right] \right\} \quad . \tag{2}$$

The exponent index n – equal to 1 for the exponential distribution – is allowed to be an integer greater than 1; μ_e and r_e are the effective surface brightness and radius, and α_n is a constant relating the effective brightness and radius to the exponential values (see Moriondo et al. 1998). In the cases for which exponential bulge fits are unsuccessful a good fit to the data is obtained with $n = 2$. The parameters of each fit are the two scalelengths, the two surface brightnesses, and the two apparent ellipticities of bulge and disk. We use the fitted disk ellipticities to determine the axial ratios a/b used for the correlations in the next sections. For 7 galaxies with particularly disturbed

[1] STSDAS is distributed by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under NASA contract NAS 5–26555.

morphology we do not manage to obtain a satisfactory fit; these objects will therefore be excluded from the following analysis. More details about the fitting procedure can be found in Moriondo et al. 1998.

4. Basic relations between disk parameters and inclination

Both the central surface brightness of the disk, $\mu(0)$, and its scalelength r_d, are expected to correlate with inclination in a way which depends on the amount of extinction present in the disk. This is also true for isophotal radii and total luminosities, which can be expressed as functions of $\mu(0)$ and r_d. From Eq. (1) a generic isophotal radius r_{iso} is defined by:

$$r_{iso} = 0.921(\mu_{iso} - \mu(0))r_d \quad ; \qquad (3)$$

whereas the total magnitude of the disk is given by

$$m = \mu(0) - 2.5\log(2\,\pi r_d^2) + 2.5\log(a/b) \quad . \qquad (4)$$

If the galaxy is completely transparent $\mu(r)$ is expected to become brighter with inclination:

$$\mu(r) = \mu^\circ(r) - 2.5\log(a/b), \qquad (5)$$

where we have denoted the face-on value with a "°"; in this case Eq. 1 implies that the disk scalelength will be independent of a/b, and from Eq. (4) it follows that m is also independent of inclination, whereas from Eq. (3) we obtain:

$$r_{iso} = r^\circ_{iso} + 2.306\, r_d \log(a/b) \qquad (6)$$

If some extinction is present in the disk Eq. (5) can be generalized as

$$\mu(0) = \mu^\circ(0) - 2.5\, C\log(a/b) \quad , \qquad (7)$$

where $0 \leq C \leq 1$, with $C = 0$ corresponding to the completely opaque case. Following G94, relationships of other photometric parameters with inclination are also parameterized as linear dependences on $\log(a/b)$. For the disk scalelength, the isophotal radius and the total disk magnitude we will have respectively:

$$r_d \;=\; r^\circ_d\,[1 + \eta\log(a/b)] \qquad (8)$$

$$r_{iso} \;=\; r^\circ_{iso}\,[1 + \delta_{iso}\log(a/b)] \qquad (9)$$

$$m_d \;=\; m^\circ_d + \gamma\log(a/b) \quad . \qquad (10)$$

Disk scalelengths are expected to be independent of inclination ($\eta = 0$) both in the case of completely transparent and completely opaque disks while they will increase with inclination if some extinction is present in the inner part of the disks (Byun et al. 1994; Bianchi et al. 1996). As opacity increases, any isophotal radius will become less sensitive to inclination than in the transparent case (δ_{iso} will decrease), whereas we expect the total luminosity to become a steeper function of inclination (γ will increase). We will assume that relations analogous to Eqs. 8-10 are appropriate to represent the trends of the corresponding bulge parameters as well.

The relations considered so far hold both for apparent and absolute quantities if we consider a single galaxy. Yet, since we are looking for average correlations in an extended sample, we will use only distance-independent quantities, i.e. the absolute ones, for which we will maintain a notation analogous to that shown above.

5. Checking for selection effects

To check for possible intrinsic differences between high and low inclination galaxies in our sample we assume that at H band galaxy disks are transparent at all inclinations at sufficiently large isophotal radii. In particular, we choose the radius where the surface brightness equals 21 H mag arcsec^{-2}, which corresponds on average to a distance of three disk scalelengths from the center and to the 22.5 mag isophote in the I band. We note that even with a B band face-on optical depth as high as 20, the triplex model by DDP and a standard extinction curve (e.g. Cardelli et al. 1989) predict an optical depth as low as 0.1 in the H band at about three disk scalelengths from the center. More refined models and simulations (e.g. Byun et al. 1994) confirm that the variation of the outer isophotal radii with inclination is largely independent of $\tau(0)$. In the hypothesis of transparency, we can estimate the face-on value of r_{21} from Eq. (6) for every galaxy in the sample. A fair sample should cover the same range in r°_{21} at all inclinations.

The quantity r°_d appearing in Eq. (6) is the face-on disk scalelength measured in the region of the galaxy where the disk is actually transparent. This in general will be different from r_d, the scalelength we obtain from our decompositions, since the latter is computed over the whole disk; we assume that at least for the galaxies which are face-on our estimate of r_d can be considered a reasonable approximation for r°_d. We correct r_d for the other galaxies using Eq. (8), with a coefficient $\eta = 0.5$. This choice for η for our H band data will be justified later on. The plot we obtain is shown in Fig. 1; here and in the rest of the paper Sa galaxies and earlier are represented by crosses, Sab and Sb by open circles, Sbc and later types by filled triangles. No obvious trend of r°_{21} with inclination appears. To make our sample as fair as possible, spanning approximately the same interval in r°_{21} at all inclinations, we exclude 12 more galaxies and restrict the following analysis to the objects whose face-on isophotal radius lies between 2.9 and 16.9 kpc (dotted lines in Fig. 1). The final sample includes 154 galaxies.

If we consider now the correlation of r_{21} (uncorrected to face-on aspect) versus $\log(a/b)$ for this subsample, we can obtain an estimate of the *average* δ_{21} coefficient; we find $\delta_{21} = 0.85{\pm}0.16$. From Eqs. (6) and (9) we see that for transparent disks, this quantity is $2.306\, r^\circ_d/r^\circ_{21}$, implying $r^\circ_{21} = 2.7\, r^\circ_d$. On the other hand, from the observed ratios r_d/r_{21} in the face-on case we can obtain an independent estimate for δ_{21}: the intercept at zero inclination of the best fit to r_d/r_{21} versus $\log(a/b)$ yields again 0.85 (± 0.03). Since this latter value depends also on the disk scalelengths derived from the image decompositions, we deduce that for face-on galaxies our estimate of r_d is not significantly different from the value expected in the case of transparency, as we have previously assumed.

For 151 galaxies of the final sample R.G. and M.H. provided 21 cm line widths, from their private database ("AGC") Further evidence that our sample is not heavily affected by selection biases is supported by the fact that we do not observe any trend with $\log(a/b)$ of the line widths, corrected for inclination.

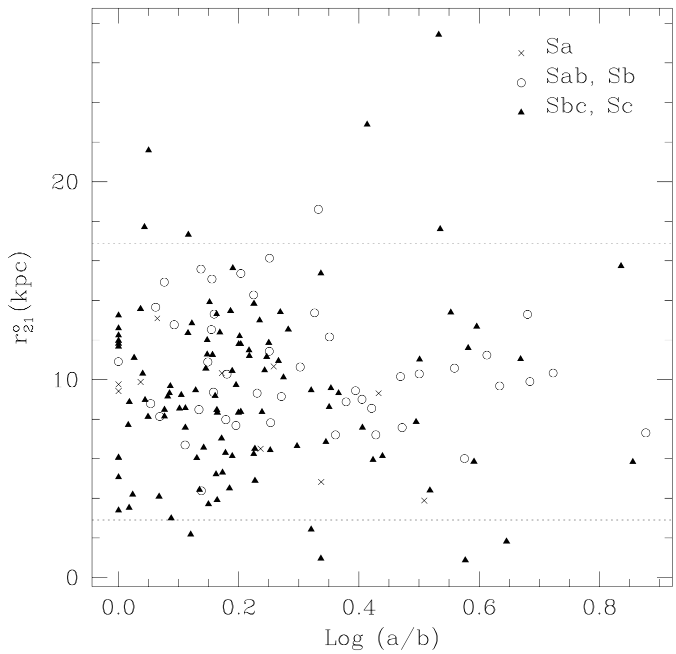

Fig. 1. Face-on corrected isophotal radius at 21 H mag arcsec^{-2} versus the logarithm of inclination. The galaxies selected for the following analysis are the ones between the two horizontal dotted lines (respectively at 2.9 and 16.5 kpc). Crosses correspond to Sa galaxies and earlier types, circles to Sab and Sb types, triangles to Sbc's and later types.

6. Observed correlations with inclination

When looking at the correlation between an observed parameter and the inclination, ideally one should analyze separately galaxies of different morphological type and absolute luminosity. Objects belonging to different classes, in fact, can be characterized by different extinction properties and therefore by different slopes in the correlation considered (G95, Tully et al 1998). Moreover, the observed parameter itself (for example the central disk brightness) is likely to depend both on the galaxy luminosity and the morphological type (G95; de Jong 1996; Morton & Haynes 1994), and not accounting for these trends would introduce additional scatter in the correlation with $\log(a/b)$. In any correlation with inclination considered for our data, we do not observe obviously different *slopes* between galaxies belonging to different classes (we will return to this point in Sect. 6.3). Therefore we assume a common slope for each correlation with $\log(a/b)$. On the other hand, as described in the next section, we account for possible trends with luminosity and morphological type of the observed parameters, i.e. we allow the *offsets* of the correlations with inclination to be different for objects of different classes. Such trends are rather evident, at least in some cases: more luminous galaxies are characterized by larger r_d's; Sa's are more compact on average (smaller r_d and brighter $\mu(0)$) than later type galaxies of the same luminosity, and so on. The H-band luminosity, in turn, appears to depend little on inclination, as we will show in Sect. 6.3, and in the next two sections we will consider the observed luminosities, uncorrected to face-on aspect.

6.1. Disk scalelength

Fig. 2a shows the correlation between H-band disk scalelengths (on a logarithmic scale) and absolute disk luminosity. In order to account at the same time for the dependence of r_d both on luminosity and on morphological type, the scalelengths are plotted after scaling each morphological type by an additive term, so that for every type, the average M_H and the average rescaled $\log(r_d)$ lie on the best linear fit to the whole (rescaled) sample. The plot is obtained iteratively: first we perform a linear regression to the observed values, after rebinning the points in groups of 12; then, for each morphological type, we scale the r_d's by an additive term so that the average scalelength for that class lies on the linear regression. The best fit is then recomputed and a new rescaling accomplished; the process is repeated until convergence. The *residuals* with respect to the final best fit are plotted versus $\log(a/b)$ in Fig. 2b. The average scalelength is added to each residual, in order to preserve the same y-axis scale; the best fit of Eq. 8 to the plot is also shown, yielding a slope $\eta = 0.41 \pm 0.17$. We remind that a correlation of r_d with inclination is to be found only if some extinction is present, at least in the inner regions of the disk.

When all the galaxies are fitted, instead of only those in the selected "fair sample", we find a slope of 0.5. This is the value we used in Sect. 5 to correct the isophotal radii to their face-on value. We find that for any value of η from 0.0 (no correlation of r_d with inclination) to 0.6 (the value derived by G94 in the I band) the plot of r°_{21} versus $\log(a/b)$ (Fig. 1) and the subsequent selection of a "fair sample" do not change much. As a consequence, if we plot the disk scalelengths versus inclination for a sample selected assuming $\eta = 0$, the value for η that we derive a posteriori from the plot is not zero but 0.56, implying that an increase of r_d with inclination is the only self-consistent possibility.

6.2. Disk surface brightness

In principle, the behaviour of the central disk surface brightness $\mu(0)$ is rather sensitive to the amount of extinction. In practice, some authors (e.g. G94; Byun et al. 1994) have questioned the actual reliability of the observed trends involving $\mu(0)$ for several reasons: the large intrinsic scatter, difficulties arising in the evaluation of $\mu(0)$ due to the presence of the bulge, a shallow dependence of $\mu(0)$ on inclination unless optical depth is very low. In our case, the use of a 2d decomposition of the brightness distribution and the fact that in the NIR extinction is actually lower than at optical bands allow us to attribute more significance to this test.

Indeed, we do find a correlation between $\mu(0)$ and $\log(a/b)$, after accounting for possible trends of the disk central brightness with respect to luminosity and morphological type in the way explained in the previous section. The plots are shown in Fig. 2c and d. The best fit to the data in panel d yields $C = 0.60 \pm 0.14$, a

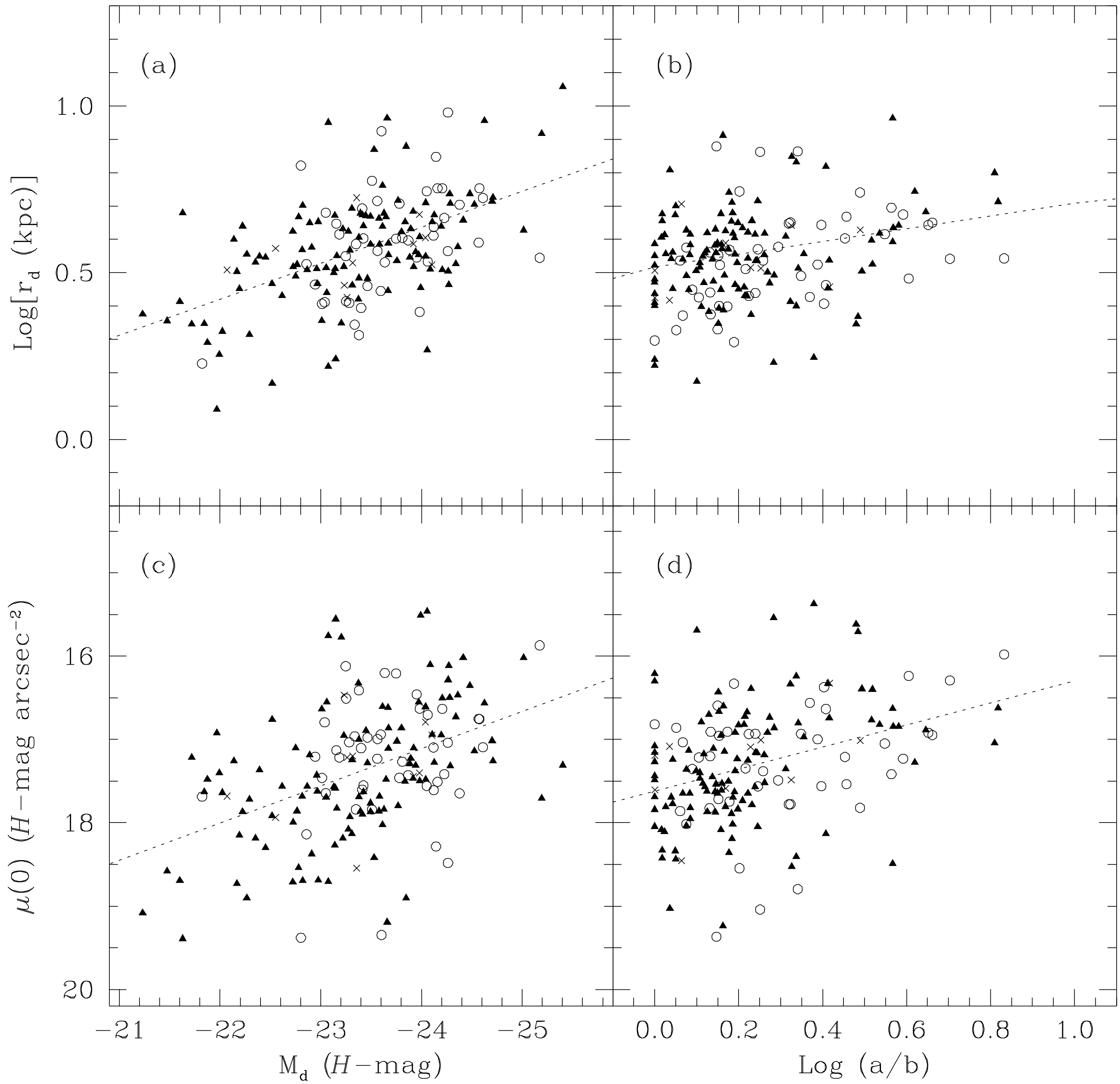

Fig. 2. a Disk scalelength plotted versus absolute luminosity, after rescaling $\log(r_d)$ for each morphology class; the straight line is the best fit to the data. **b** residuals from the best fit in panel a plotted versus $\log(a/b)$; the average scalelength is added to each residual in order to preserve the same y-axis scale. The best fit to r_d versus $\log(a/b)$ is also shown. **c** and **d** the same correlations for the central disk surface brightness.

rather high increase with inclination which tends to exclude high disk opacities. This value is consistent with two published estimates of the coefficient, both derived using average disk surface brightnesses from aperture photometry. In particular Peletier & Willner (1992) confined C_H between 0.6 and 0.8, and deduced a central face-on optical depth of about 0.2 using a DDP sandwich model. Boselli & Gavazzi (1994) found $C_H = 0.65$, independent of morphological type. The face-on central surface brightness turns out to be 17.6 H-mag arcsec^{-2} with a dispersion of 0.7.

6.3. The Holmberg test

Let us consider now the so-called Holmberg test (Holmberg 1958, 1975), i.e. the correlation between inclination and the average surface brightness within the circular aperture defined by a certain isophotal radius. An observed trend of this quantity with inclination could be interpreted as the signature of significant opacity in the disks. However, as stated by G94, a trend is expected also in the case of transparent galaxies because the isophotal radius is an increasing function of inclination (ex-

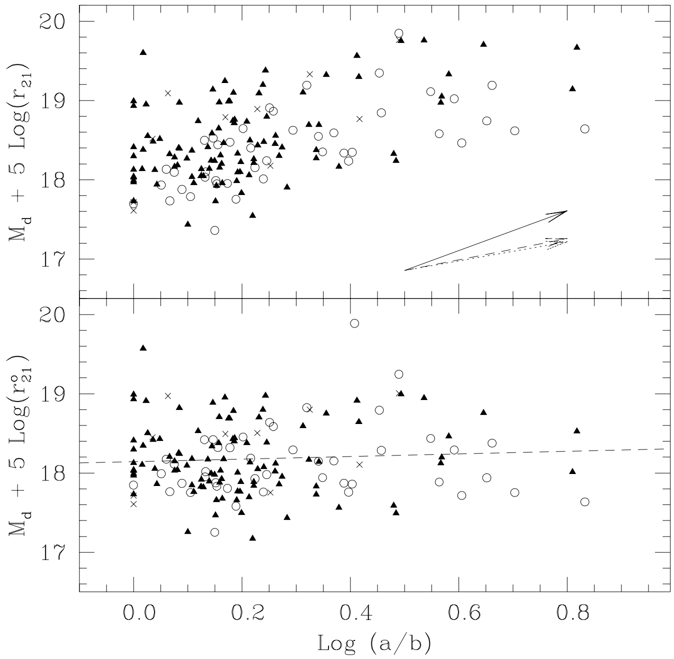

Fig. 3. Top panel: Average surface brightness within r_{21} versus $\log(a/b)$. The three arrows represent the trend expected for different opacities: the solid arrow is for completely opaque galaxies, the dotted arrow for completely transparent ones, the dashed arrow is derived from the observed slopes of r_d and $\mu(0)$ versus inclination. Bottom panel: average surface brightness within r°_{21} versus $\log(a/b)$, with the best fit to the data points.

cept in the case of *completely* opaque disks), so that the surface brightness tends to decrease at high inclinations because it is estimated using a larger aperture.

Fig. 3 (top panel) displays the correlation found for our data; in this case, each morphology class was scaled by an additive term such as to have a common average on the y axis. Also shown are the expected slopes in the case of a completely transparent disk (dotted arrow), a completely opaque one (solid arrow), and the behaviour expected when isophotal radius and disk scalelengths vary with inclination according to the relations described in the previous sections. The three slopes are computed for a pure exponential and assuming $r^{\circ}_{21}/r^{\circ}_{d} = 2.7$. We note that the coefficients derived from our data yield a trend which is nearly the same, in terms of average surface brightness, to the one expected for completely transparent galaxies. Actually, as already stated by G94, this kind of correlation is not particularly sensitive to the amount of internal extinction, and the scatter in the plot is too large to distinguish reliably between the different cases.

Following G94, we also consider a modified version of the Holmberg test in which the surface brightness is calculated within the *face-on* value of the isophotal radius. In particular, in the bottom panel of Fig. 3, we plot the disk magnitude plus $5 \log r^{\circ}_{21}$ versus the inclination, and the best fit to the data. Since r°_{21} – computed using Eq. 9 with $\delta_{21} = 0.85$ – is by definition independent of inclination, the slope of this plot is the coefficient γ in Eq. (10); the value of γ corresponds roughly to the correction for the total magnitude from edge-on to face-on aspect. We find little correlation between the two quantities ($\gamma = 0.16 \pm 0.22$), which, at first sight, is the signature of nearly complete transparency. Actually, this small correlation is consistent with the other trends observed: the brightening of $\mu(0)$ with inclination in our galaxies is smaller than in the transparent case, yet the increase of r_d – which does not occur if disks are optically thin – contributes to raise the value of the total luminosity within r_{21}, making the average surface brightness behave very much like in the case of complete transparency. Quantitatively, if we parametrize the correlation between r_d and (a/b) as a power law, instead of using Eq. 8, in particular if we write

$$r_d = r^o_d \left(\frac{a}{b}\right)^{\alpha} \quad , \tag{11}$$

it can be easily demonstrated that $\gamma = 1 - C - 2\alpha$. For our data we find $\alpha = 0.2 \pm 0.05$, yielding $\gamma = 0 \pm 0.15$, consistent with the value obtained from Fig. 3.

In recent work, Tully et al. (1998) derived estimates for the extinction correction to face-on both in the optical and in the NIR (K' band), as a function of galaxy luminosity. Assuming $H - K' \sim 0.2$ mag, and since the median absolute luminosity for the galaxies in our sample is -23.7 $H-$mag, we derive from their Eq. (6) $\gamma_{K'} = 0.26$, a value which is consistent with ours, if we assume the difference between $\gamma_{K'}$ and γ_H to be negligible. A dependence of the amount of internal extinction on the galaxy luminosity is also found by G95. For our galaxies we do not observe any trend of this kind, but we note that our sample covers a limited range in absolute magnitude (about three magnitudes, and even less when considering the galaxies at high inclination). Moreover, for galaxies as luminous as ours (we estimate our I-band absolute magnitudes to be brighter than -20), the G95 data suggest only a rather shallow dependence of extinction on luminosity (see e.g. their Fig. 7).

6.4. Bulge parameters

We look now for correlations of the H-band bulge parameters with inclination, in particular of the bulge effective radius r_e, effective surface brightness μ_e and absolute magnitude M_b, using the same approach outlined for the disk parameters in the previous sections. We find a small increase of r_e with inclination, and little or no correlation for μ_e and M_b. In particular, if we define three coefficients η_b, C_b and γ_b using the same relations adopted for the disk (Eqs. 8–10), we derive from the best fits to the data the following values:

$$\eta_b = 0.24 \pm 0.16 \tag{12}$$
$$C_b = 0.04 \pm 0.16 \tag{13}$$
$$\gamma_b = 0.09 \pm 0.55 \quad . \tag{14}$$

The bulge-to-disk ratio as well exhibits no significant dependence on inclination.

In this case a straightforward interpretation of the results is more difficult than for the disk parameters: in fact the bulge and the dust are characterized by completely different spatial distributions, respectively a peaked and compact spheroid and an extended thin disk, so that in general extinction will not be uniformely distributed throughout the spheroid. In the transparent case, however, we would expect the scalelength to be independent of inclination, and the effective surface brightness to increase with $\log(a/b)$ (though not as much as $\mu(0)$, due to the lower intrinsic ellipticity of the bulge). Since this is not the case for our sample, we interpret the different observed behaviour, again, as the effect of some extinction, that needs to be present at these wavelengths, at least in the central galaxy regions.

6.5. $I-H$ colour profiles

For 68 of our galaxies, I band brightness profiles are available from the ScI sample of Haynes et al. (in preparation); for these objects, we compute $I-H$ colour profiles. To reduce them to a common radial scale, we normalize the distance from the center with the value of the disk scalelength, measured in the H band and corrected to face-on aspect using Eq. (8).

A reddening of the observed colours with inclination at a given radius and for a fixed stellar population is expected if (and only if) some dust is present, since the optical depth along the line of sight increases with inclination, and at shorter wavelengths the scattering is more effective in removing photons traveling within the plane of the disk. Since the dust is concentrated towards the center of the galaxy it will also produce a radial colour gradient, making the outer regions of the galaxy look bluer. However, a contribution to such a gradient can also be provided by a variation of metallicity or average stellar population with radius. Similarly, higher extinction, metallicity, and different stellar content, can be invoked to explain the redder colours of high luminosity galaxies (Gavazzi, 1993; Tully et al. 1998). On the other hand, a correlation of colour with inclination provides direct and unambiguous evidence for reddening by dust. Fig. 4 shows the average $I-H$ radial profiles for our sample in three bins of absolute magnitude. As expected, they become bluer with increasing radius, and brighter galaxies tend to be redder at any given radius.

We inspect for trends of $I-H$ with inclination in three radial bins: within one disk scalelength, between one and two, and between two and three r_d's respectively. We exclude the region inside 1/3 of r_d, where different seeing between I and H and the presence of a bulge can produce extremely high "local" colour gradients. Since the reddening of colour with increasing luminosity would introduce scatter in the correlation with inclination, in each radial bin we obtain a best fit to the colour-luminosity relation and plot the residuals versus the inclination. We do not observe any difference in colour between early and late-type spirals; therefore in this case we didn't rescale the different morphological types. Fig. 5 (left hand panels) shows the observed colour-luminosity relations in the 3 radial bins with a best fit for each bin; the slopes are -0.12 ± 0.01, -0.11 ± 0.02 and -0.08 ± 0.03 respectively; the sign of the slopes is the one expected (redder colour with increasing luminosity). In the right hand panels we plot the residuals of these correlations versus $\log(a/b)$. In each panel the average colour for that particular bin is added to each residual, to preserve the same y-axis scale;

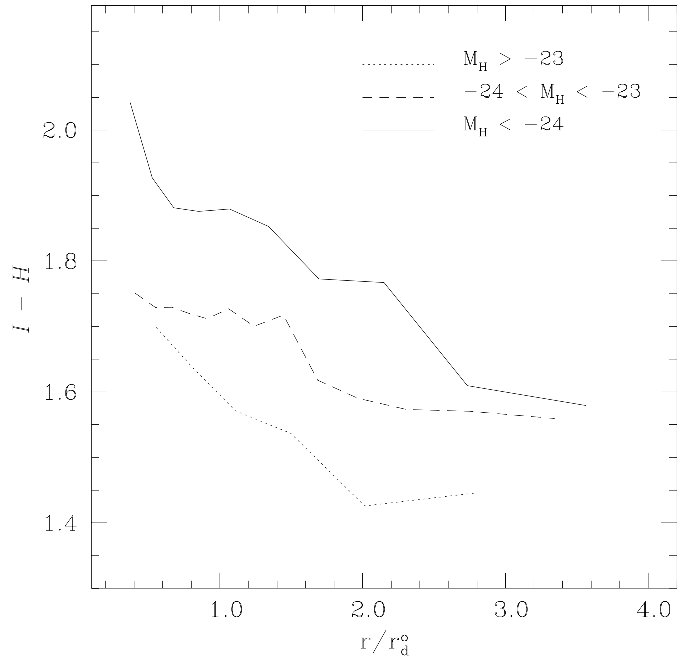

Fig. 4. $I-H$ radial colour profiles averaged in three bins of absolute magnitude. Radii are normalized with the disk scalelength corrected to face-on aspect.

the best fits to the data are also shown. As expected we find that more inclined galaxies tend to be redder. The slopes of the best fits are 0.34 ± 0.04 mag, 0.56 ± 0.07, and 0.6 ± 0.1 respectively.

If we consider the average disk colours, the slope in the correlation between colour and inclination amounts to $\gamma_I-\gamma_H$, and we find this slope to be 0.46 $\pm$0.14. Again, we can compare our result to the values found by Tully et al. (1998) and G94. The median $I-H$ for our sample is 1.74, yielding for the I band luminosity a value of about -22. Eq. (5) in Tully et al. then gives $\gamma_I=1.05$, which is also the value found by G94 for their sample. Our data seem to suggest a slightly lower value for γ_I (i.e. lower extinction), for which we can set an upper limit of about 0.9 from the colour-inclination slope and from the value of γ_H derived in the previous section.

6.6. Color gradients and inclination

We also measured colour gradients by fitting to each profile a straight line, still excluding the points inside 0.3 r_d°. Fig. 6 shows the gradients obtained for this subsample plotted versus inclination. Assuming that an exponential disk fits well both the I and H brightness distributions, it can be easily shown that

$$\frac{d\,(I-H)}{d\,\rho}=1.086\left(\frac{r_H}{r_I}-1\right) \tag{15}$$

where we have denoted with r_I and r_H the disk scalelengths in the two bands, and $\rho=r/r_H$ is the radius in units of the H band disk scalelength. If we parametrize the dependence of r_d on inclination with Eq. 11, we obtain

$$\frac{d\,(I-H)}{d\,\rho}=1.086\left(\frac{r_H^o}{r_I^o}\left(\frac{a}{b}\right)^{\alpha_H-\alpha_I}-1\right)\quad . \tag{16}$$

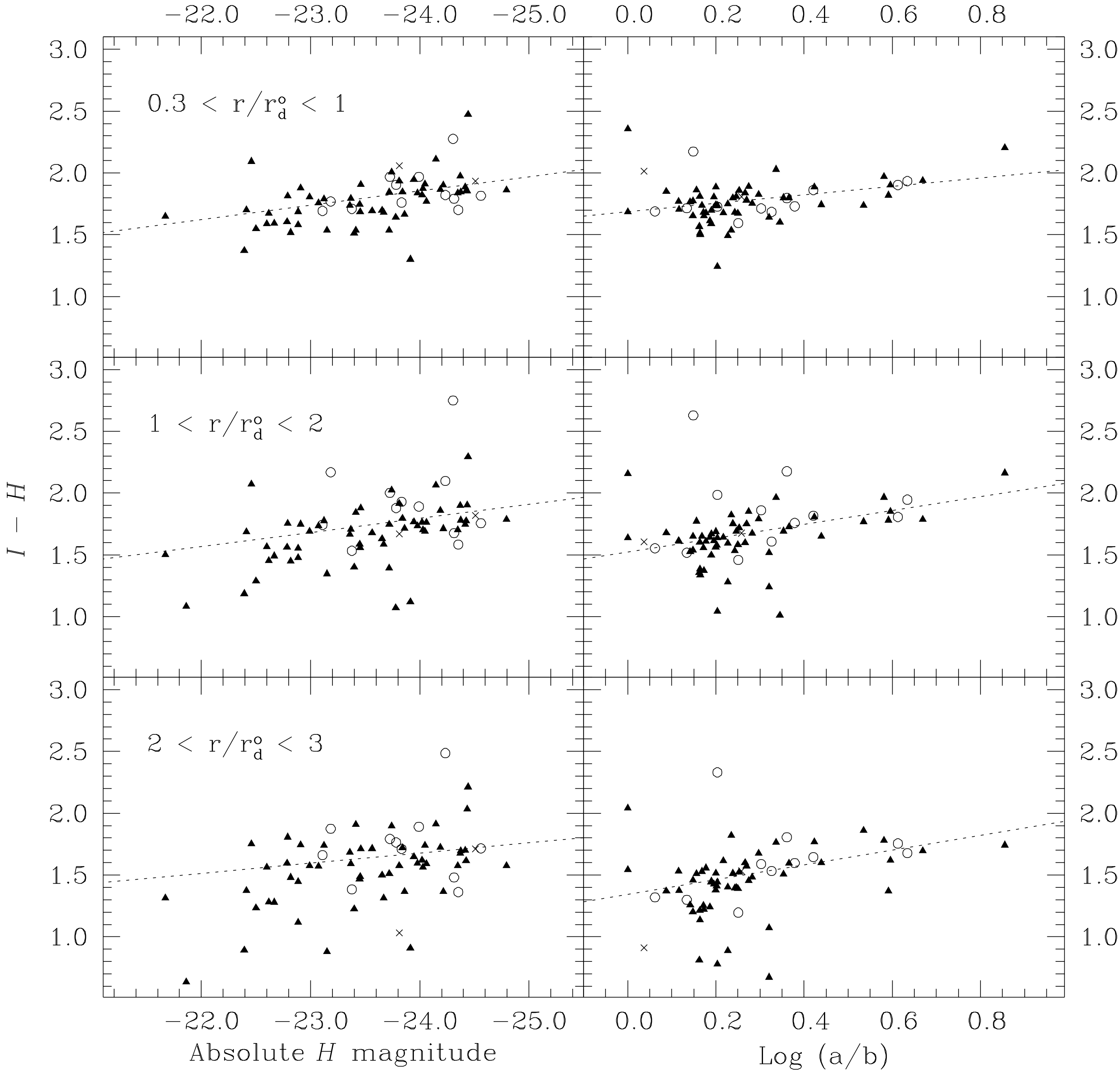

Fig. 5. Left hand panels: colour-luminosity relations. In each panel, from top to bottom, we plot $I - H$ colours averaged in a different radial bin. The best fit to the data are also shown. Right hand panels: the residuals from the best fit to the colour-luminosity relations in the left hand panels are plotted versus the inclination. In each panel the average colour for that particular bin is added to each residual, to preserve the same y-axis scale. The best fits to the data are also shown.

The fact that a negative gradient is almost always detected implies that on average r_H is smaller than r_I; moreover, this difference is about the same at all inclinations – amounting to $10 \sim 20\%$ – which is what we expect if the disk scalelengths correlate in a similar way with inclination in both bands, i.e. $\alpha_H \simeq \alpha_I$. If any correlation is to be found in Fig. 6, it is in the sense of smaller gradients for high inclinations, implying $\alpha_H > \alpha_I$ from Eq. (16). Looking at Fig. 7 in G95 this seems actually to be the case for galaxies brighter than -20 I-mag, for which a value of $\alpha_I \simeq 0.1$ is appropriate, whereas we found $\alpha_H = 0.2$. Note that from the same figure it turns out that the dependence on inclination of disk scalelengths is steeper (α is higher) for galaxies of low luminosity, which the authors claim to be *less* extincted. The fact that α is higher also in the H band where extinction is certainly lower is therefore a confirmation of G95's result. A best fit to the data points in Fig. 6 (dashed line) yields $\alpha_H - \alpha_I = 0.11 \pm 0.04$, and a rather accurate estimate for the ratio $r^o_H/r^o_I = 0.81 \pm 0.03$.

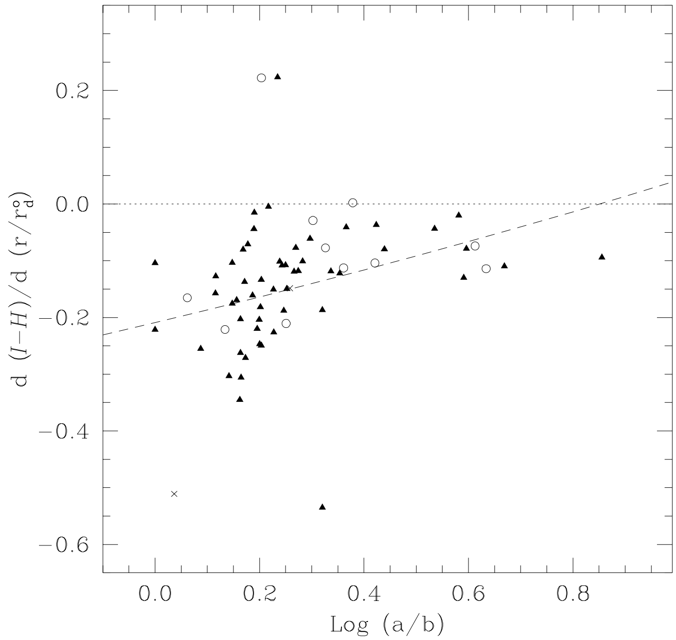

Fig. 6. Radial colour gradients versus $\log(a/b)$. The dashed line is the best fit to the data assuming a power-law dependence of r_d on the axial ratio a/b both in I and H.

7. Disk opacity in the NIR

Some qualitative statements can be made on the basis of the correlations shown above. It appears that some of the parameters which describe the brightness distribution of a galaxy are affected by the presence of interstellar dust also in the NIR. At these wavelengths, however, the effect of extinction on most observable quantities is quite small. The best evidence for the presence of extinction is in the correlation between disk scalelength and inclination – which turns out to be similar to the one existing in the I band (Sect. 6.6 and Sect. 6.1) – and in that between $I - H$ colour and inclination. On the other hand, the behaviour of the disk central brightness is not very different from what we expect in the case of transparency; such a correlation, as pointed out by Byun at al, 1994, is to be seen only when opacity is low. Moreover, we find little variation of the total luminosity with inclination, and the correction from edge-on to face-on for the total magnitude is about 0.15 mag on average confirming that extinction in the NIR , though detectable, is not conspicuous even at high inclinations.

7.1. Simulating absorption by dust

In order to better quantify our estimate of optical depth in the disks, we simulate a set of brightness distributions affected by absorption by dust for a range of inclinations and different values of the central optical depth. We adopt a model galaxy in which dust and stars are distributed exponentially both in the radial and "vertical" direction, like in the triplex model by DDP, but we assume the dust scalelength to be larger than r_d, following Peletier et al. (1995), the results of two recent works by Xilouris et al. (1997, 1998), and of Nelson et al. 1998. In particular our dust disks are 1.5 times larger than the stellar ones. The models are major-axis brightness profiles computed according to the approximate analytical solution for radiative transfer in a dusty disk described in DDP. We consider pure disks (no bulge component) with dust-to-stars scaleheight ratio ζ = 0.25, 0.5, or 0.75, and $\tau_H(0) \leq 2$. Scattering effects are not included. The profiles are fitted with exponentials excluding the inner part, within 0.3 disk scalelengths, i.e. the region in our galaxies where the bulge is usually the brighter component. To make the fitting process as similar as possible to the one we performed on real galaxies, a proper weighting is given to the various points of the profile in order to simulate the typical errors in our data. Since our sample is not uniformly distributed in $\log(a/b)$, we define a set of inclinations for the models by rebinning the values for the real data in groups of 12 galaxies each. The highest inclination bin is centered at 80°, where the numerical approximations in the model are still reasonably accurate (see DDP and G94).

We also compute a set of models to simulate the bulge brightness profiles in the region where they are usually brighter than the disk. For our galaxies the bulge is in general well represented by an exponential, and it dominates the brightness distribution at any inclination within approximately two effective radii (i.e. about three bulge scalelengths r_b, or 0.3 disk scalelengths). The median intrinsic ellipticity is 0.4. A satisfactory modeling of the bulge-dominated region of a galaxy should in principle be carried out using two dimensional brightness distributions, to analyze the information provided by the asymmetries, due to extinction, between the two halves of the galaxy image. It should also account for the presence of the underlying disk distribution. In our case we will consider our simple model of the major-axis surface brightness profile only as a rough check for the observed trends of the bulge parameters with inclination. In this perspective we adopt the same type of model we used for the disk (the product of two exponentials, along the radial and vertical direction respectively), though a density distribution characterized by ellipsoidal isophotal surfaces would be more appropriate to represent the spheroidal shape of the bulge. For this set of models we choose a dust scalelength 13 times larger than r_b; using the typical intrinsic bulge ellipticity (0.4) and the bulge-to-disk scalelength ratio (~ 0.1) of our sample galaxies, we also transform the dust-to-stars scaleheights adopted for the disk, namely 0.25, 0.5, and 0.75, into 0.35, 0.7, and 1 respectively.

7.2. Disk and bulge parameters

Fig. 7a–c shows the expected slopes of the correlations of disk scalelength, central brightness, and total luminosity with inclination (coefficients η, C, and γ). The coefficients are plotted as a function of central optical depth. In each panel the dashed line, the solid line, and the dotted line correspond to the simulations with $\zeta = 0.25$, 0.5 and 0.75 respectively. The shaded areas are the estimates of the coefficients derived from our sample at 1 σ confidence level.

It turns out that all the observed coefficients are consistent with the models in a range of central optical depths. In particular, from panel b, we can set a lower limit for $\tau_H(0)$ around 0.3 regardless of the thickness of the dust layer, since the three coefficients considered exhibit little dependence on ζ for $\tau_H(0) \lesssim 0.5$. From panel c, on the other hand, we derive an upper limit to the optical depth around 0.5 again roughly independent of ζ. We note that our lower limit implies a larger $\tau_H(0)$ than the values around 0.1 suggested by the results in Xilouris et al. (1997, 1998). Such values, however, are derived for two particular edge-on galaxies and not from a statistical analysis, and we do not consider the discrepancy particularly worrisome. Adopting the extinction curve reported by Gordon et al. 1997 for the Milky Way, our limits for $\tau_H(0)$ imply a central optical depth between 0.9 and 1.4 in the I band, between 1.8 and 3 in the V band, and between 2.4 and 3.9 in the B band. In agreement with most of the recent works on the subject, therefore, our data suggest that spiral disks are characterized by a moderate opacity also at optical wavelengths. In particular the presence of a significant extinction in the outer disk regions can be safely ruled out, except in the case of extremely inclined galaxies. On the other hand, the extinction corrections derived from our data cannot be easily extrapolated to the B or V band on the basis of the extincton curve alone, since they also depend on the exact geometry of dust and stars, and on the wavelength-dependent effect of scattering (see for example Byun et al. 1994).

In our model we assumed a dust disk larger by 50% than the stellar one. If we adopt equal scalelengths for the two components we find that the predicted slopes are consistent with our data for slightly higher values of $\tau_H(0)$, namely between 0.4 and 0.8. If we consider instead an even more extended dust layer, in particular if the dust scalelength in twice as large as r_d, again we find agreement between models and data for $\tau_H(0)$ around 0.3.

Fig. 8a–c is the analogous of Fig. 7a–c for the bulge parameters. Comparing the model predictions in the two figures the largest difference is to be found in the behaviour of the coefficient C, which for the disk is equal to 1 in the transparent case and then decreases tending to zero as $\tau(0)$ increases. For the bulge the apparent axial ratio is always $\geq b/a$, so that in the transparent case $C_b < 1$; moreover, since the dust distribution is much more extended than the bulge in the radial direction, for sufficiently high optical depths the surface brightness along the major axis becomes *fainter* with increasing inclination, yielding $C_b < 0$.

As explained in the previous section these simulations are to be considered less reliable than the ones carried out for the disks, and actually there are no values of the central optical depth for which we have agreement between models and data for all the three correlations considered, at 1 σ confidence level. We note however that at 2 σ any $\tau_H(0) \lesssim 0.5$ is consistent with the data; as was the case for Fig. 7a–c this is true regardless of the dust-to-stars scaleheight ratio. This range of optical depths, in turn, is consistent with the one derived from the disk correlations, so that we can consider the results from these tests as a confirmation – though at a lower confidence level – of our previous findings.

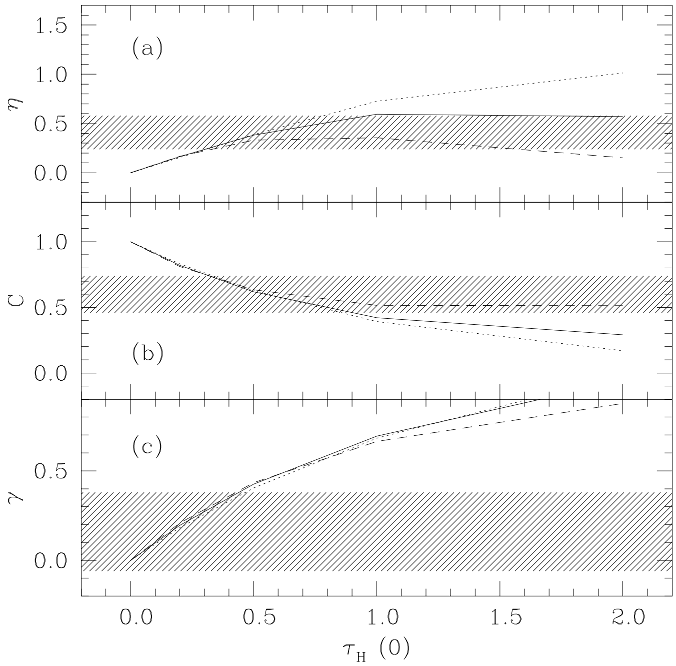

Fig. 7a–c. From top to bottom: H-band η, C, and γ coefficients versus central optical depth. Dashed lines represent simulations with dust-to-stars scaleheight ratio $\zeta = 0.25$; for thin solid lines $\zeta = 0.5$, and for dotted lines $\zeta = 0.75$. The shaded areas are the ranges we derive from the observed disk parameters at 1 σ confidence level.

7.3. $I - H$ colours

Fig. 9 shows the dependence on $\tau_H(0)$ of the simulated slopes of $I - H$ colour versus $\log(a/b)$ in the three radial bins considered for the real data. The values we derive from our galaxies are represented by the shaded areas. In the simulations τ_I is assumed to be 2.87 times the value in the H band, according to the value reported by Gordon et al. (1997) for the Milky Way. From this plot, we infer that the slopes derived from our data are consistent with the limits previously set on $\tau_H(0)$ (0.3 $\sim$ 0.5) only if $\zeta < 0.5$. For thicker dust layers the dependence of the colour on inclination tends to be too steep within r_d, unless we increase the central optical depth above 1. This result holds regardless of the radial extension of the dust distribution with respect to the stellar scalelength. A thick dust distribution appears unlikely also because of the little difference observed in the dependence of r_d on inclination between the H and I band, i.e. for two optical depths differing by about a factor of three (see Sect. 6.6). From Fig. 7a, we see that η is constant or decreasing with increasing τ only for *low* values of ζ (we neglect differences in ζ between H and I: e.g., Xilouris et al. 1997 find this ratio to be fairly constant from K to B for NGC 2048).

7.4. *Is scattering important?*

In our simple model for an internally-extincted galaxy, we have neglected the effect of scattering of radiation by dust; roughly speaking, this means that for a given amount of dust (i.e. for a given $\tau(0)$) our model galaxy is less luminous than a real galaxy

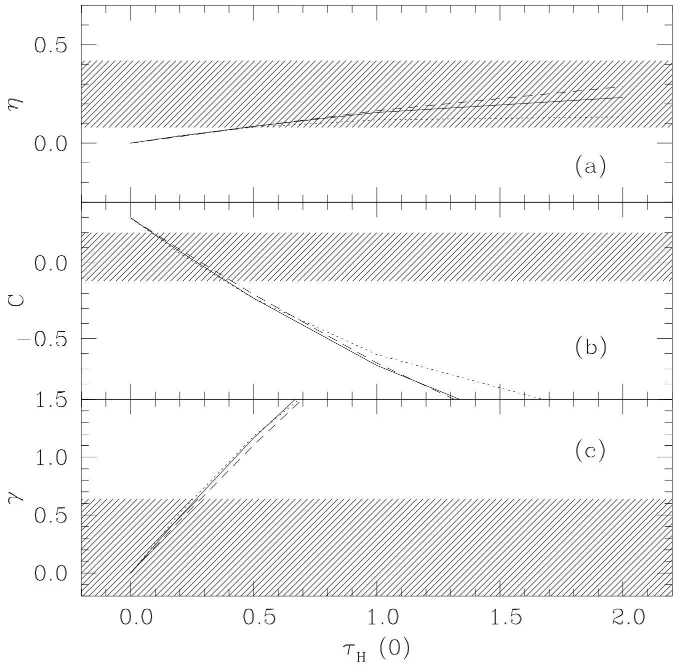

Fig. 8a–c. From top to bottom: H-band η_b, C_b, and γ_b coefficients versus central optical depth. Dashed lines represent simulations with dust-to-stars scaleheight ratio $\zeta = 0.35$; for thin solid lines $\zeta = 0.7$, and for dotted lines $\zeta = 1$. The shaded areas are the ranges we derive from the observed bulge parameters at 1 σ confidence level.

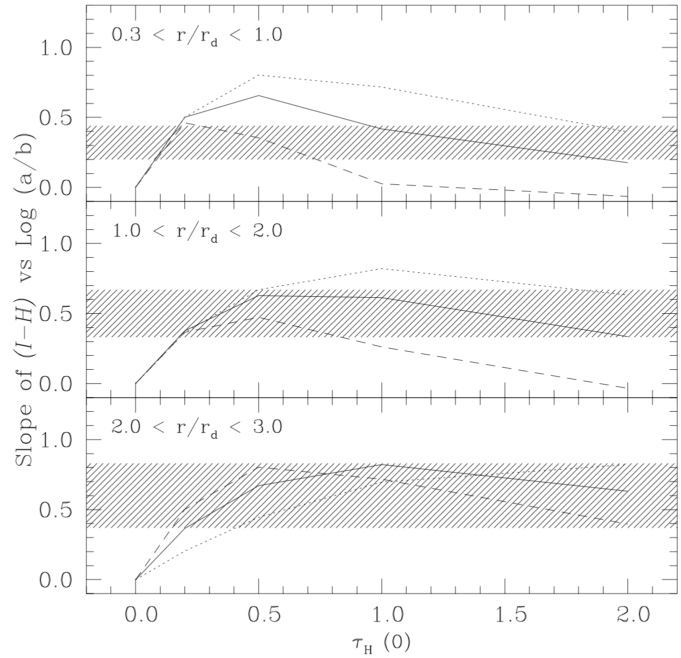

Fig. 9. Slope of the correlation of $I - H$ colour versus inclination, plotted versus central H-band optical depth, in three radial bins. Dashed lines represent simulations with dust-to-stars scaleheight ratio $\zeta = 0.25$; for thin solid lines $\zeta = 0.5$, and for dotted lines $\zeta = 0.75$. The shaded areas are the ranges we derive from our data at 1 σ confidence level.

with the same structural parameters. How does this affect the conclusions derived from our simulations? We note that we are not interested on how scattering affects the observed quantities, but on how it affects their correlations with inclination. A few Monte Carlo simulations of a dusty spiral galaxy kindly provided by S. Bianchi allowed us to quantify approximately the differences introduced by scattering in the observed H-band brightness distribution at low and high inclinations. The code which performed the simulations, described in Bianchi et al. (1996), produces a set of images at different inclinations for a given galaxy computing the radiative transfer without introducing any approximation and including both absorption and multiple scattering by dust. For every simulated galaxy image the corresponding image including only absorption was also computed. A comparison of the two sets of images (with and without scattering) for a galaxy with the average structural properties of our sample and a central optical depth $\tau_H(0) = 1$ reveals that the contribution by scattering to the observed surface brightness is slightly higher at low inclinations and increasing toward the center. Yet, the implied corrections to r_d and $\mu(0)$ are rather insensitive to inclination when compared to the observed variations of these parameters with $\log(a/b)$. We estimate the correction to the central disk brightness due to scattering to be roughly 0.06 H-mag arcsec^{-2} larger in the face-on case than in the case of a highly inclined galaxy ($\sim 80^\circ$), and the decrease in r_d to be around 2% larger in the face-on case. Both these corrections are negligible, since the observed correlations with inclination for these parameters imply a brightening of ~ 1.15 mag for $\mu(0)$, and an increase of $\sim$ 30% for r_d, between face-on and 80° inclination. The difference in the scattering correction to the total magnitude is more significant (~ 0.04 mag) given the small variation of this quantity with $\log(a/b)$, but still rather small. Moreover, since the central optical depth is likely to be less than 1 in the H band, the actual corrections are probably even smaller than these. The effect of scattering is likely to be more important when considering the correlations with inclinations of the *bulge* parameters, given the little dependence on $\log(a/b)$ we find for all of them, and the highly concentrated bulge brightness distribution. On the other hand, in this case our model is a rather poor approximation anyway, and we considered its predictions only as a rough confirmation of the results derived from the disk parameters.

In conclusion, we expect that the inclusion of scattering in the model would not produce significant changes in our estimate of $\tau_H(0)$.

8. Summary

In this paper, we have derived NIR (H band) structural parameters for a sample of 173 spiral galaxies in the Pisces-Perseus supercluster, using a bi-dimensional decomposition of the galaxy images. We have subsequently analyzed the correlations of such parameters with inclination in order to detect possible effects of internal extinction and estimate the relative corrections to face-on aspect. For 68 galaxies of the sample $I - H$ colour profiles are also available, which were used to the same purpose. The main results of this work are:

1) The effect of internal extinction in the H band, though small, can be detected. In particular the increase of the average disk scalelength and of the disk $I-H$ colours with inclination can be attributed to the presence of the dust.

2) We find little dependence of the total disk luminosity on inclination. We derive an average correction of about 0.15 mag from edge-on to face-on aspect in the H band. We find this result to be consistent with the correlations we find for r_d and $\mu(0)$ versus inclination. Little or no correlation with inclination is found for the bulge parameters.

3) Comparing our results with the predictions of a simple model for extincted galaxies, we deduce that the average central optical depth in the H band is between 0.3 and 0.5 if the dust scalelength is 50% larger than r_d. The simulations also suggest that the ratio of the dust-to-stars scaleheights is on average lower than 0.5. The effect of scattering on the various correlations considered is found to be negligible at these wavelengths.

Acknowledgements. We would like to thank S. Bianchi for having provided Monte Carlo simulations of dusty spiral galaxies, the referee - Dr. P.C. van der Kruit, and C. Giovanardi and L. Hunt for useful comments and suggestions. This research was partially funded by ASI Grant ARS–96–66. Partial support during residency of G.M. at Cornell University was obtained via the NSF grant AST96-17069 to R. Giovanelli.

References

Andredakis Y.C., Peletier R.F., Balcells M., 1995, MNRAS 275, 874
Bianchi S., Ferrara A., Giovanardi C., 1996, ApJ 465, 127
Boselli A., Gavazzi G., 1994, A&A 283, 12
Burstein D., Haynes M.P., Faber S.M., 1991, Nat 353, 515
Byun Y.I., Freeman K.C. 1995, ApJ 448, 563
Byun Y.I., Freeman K.C., Kylafis N.D., 1994, ApJ 432, 114
Cardelli A.J., Clayton G.C., Mathis J.S., 1989, ApJ 345, 245
Corradi R.L.M., Beckman J.E., Simonneau E., 1996, MNRAS 282, 1005
Davies J.I., 1990, MNRAS 244, 8
Davies J.I., Phillips S., Boyce P.J., et al., 1993, MNRAS 260, 491
de Jong R.S., 1996, A&A 313, 45
de Vaucouleurs G., de Vaucouleurs A., Corwin Jr. H.G., et al., 1991, Third Reference Catalogue of Bright Galaxies (Springer-Verlag, New York).
Disney M., Davies J., Phillips S., 1989, MNRAS 239, 939
Gavazzi G., 1993, ApJ 419, 469
Giovanelli R., Haynes M.P., Salzer J.J., et al., 1994, AJ 107, 2036
Giovanelli R., Haynes M.P., Salzer J.J., et al., 1995, AJ 110, 1059
Gordon K.D., Calzetti D., Witt A.N., 1997, ApJ 487, 625
Holmberg E., 1958, Medn. Lunds astr. Obs., Ser. 2, No. 136
Holmberg E., 1975, in Stars and Stellars Systems, Vol. IX, A. Sandage, M. Sandage, J. Kristian eds. (University of Chicago, Chicago).
Jansen R.A., Knapen J.H, Beckman J.E., et al., 1994, MNRAS 270, 373
Knapen J.H., van der Kruit P.C., 1992, A&A 248, 57
Moriondo G., Giovanardi C., Hunt L.K., 1998, A&AS 130, 81
Morton R.S., Haynes M.P., 1994, ARA&A, 32, 115
Nelson A.E., Zaritsky D., Cutri R.M., 1998, astro-ph/9803161
Peletier R.F., Willner S.P., 1992, AJ 103, 1761
Peletier R.F., Valentijn E.A., Moorwood A.F.M., et al., 1995, A&A 300, L1
Sèrsic J.L., 1968, Atlas de Galaxias Australes (Cordoba: Observatorio Astronomico)
Tully R.B., Pierce M.J., Huang J., et al., 1998, astro-ph/9802247
Xilouris E.M., Kylafis N.D., Papamastorakis J., et al., 1997, A&A 325, 135
Xilouris E.M., Alton P.B., Davies J.I., et al., 1998, A&A 331, 894
Valentijn E.A. 1990, Nat 346, 153