STATISTICAL TESTS FOR OPACITY

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1. Introduction

Here, I will discuss recent statistical tests related to opacity studies. In essence, most of these tests are "inclination tests", *i.e.* studies how particular photometric parameters depend on the inclination angle of the galactic disks with respect to the line of sight of the observer.

My main conclusion is that the current literature on this subject is less controversial than often stated. At various places of the analysis the conclusion is drawn that observational data can be best understood when, next to a cirrus-like dust component which follows the radial distribution of the stars, a second component exists with an exponential scalelength larger than that of the stars. This second component has a typical optical depth[1] $\tau^B_{face} \sim 1$ at the effective radii of galaxies (and beyond), as suggested in my 1990 paper (hereafter V90). Overall face-on values of $\tau^B \sim 1$ will result in galaxies that appear optically thick and an overall optical depth > 1 will be common for disks that are inclined with respect to the external observer.

Obviously, overall values of the optical depth around unity will affect the determination of intrinsic luminosities, but possibly even more important related astrophysical questions include:

- what is the nature of the extended component?
- does the existence of extended dust components lead to mass models, which solve the flat rotation curves of spiral galaxies, without invoking the existence of dark haloes? (González-Serrano and Valentijn, 1991, = GV91, and Valentijn 1991, = V91).

[1]optical depth defined as the ratio between the projected thickness of the disk and the mean free path of photons

2. The Opacity Study Ladder

The analysis of inclination tests in relation to the opacity problem involves a large amount of steps, which are summarized in Figure 1.

2.1. SAMPLES, PARAMETERS

After obtaining a sample of galaxies with detailed surface photometry (ESO-LV in our work) both a parameter and a sub-sample have to be selected. Today's detailed photometric catalogues actually allow the usage of at least 8 different photometric parameters and 8 different ways to select a sample (e.g. magnitude selected, diameter selected, surface brightness selected, redshift selected, V/V_{max}volume selected). Each of these parameter-sample combinations has its own problems regarding selection effects and possible biases. The unique logistics of selection effects for each of these combinations implies that one can not simply transfer a selection effect noted for one parameter-sample combination to another combination. It is this wealth of ways to perform the inclination test, and the variety of effects for different parameter-sample combinations that has lead to the diversity of the modern literature on this subject (see V91b and V94 for a more extensive discussion). There is no way to discuss all the different combinations here, (an attempt is made in V94), but instead, I will mention a few of the most remarkable results.

The Holmberg approach involved a plot of the *projected* surface brightness ($B + 2.5loga^2$, with a the length of the observed major axis) versus the apparent axial ratio. Both B and a^2 depend on the value of the optical depth, but in a reverse way and with an approximately equal amplitude for most models. Thus, the projected surface brightness is not a very critical parameter for measuring the optical depth, and the Holmberg graph is not providing much statistical information on the opacity problem.

More powerful are parameters which involve the *local* surface brightness of galaxy disks. The local surface brightness is a distance independent parameter, which avoids a number of distant dependent selection effects. One of the strongest inclination tests results is, perhaps, the constancy of the local surface brightness at the effective radius[2]. In Fig. 2 data are plotted for a sample of Sb galaxies, for which detailed radial surface brightness profile fits indicate that these systems have a perfect exponential light profile ($N \sim 1$ when fitting $I(r) \sim exp(-r/r_\alpha)^N$). For pure spheroïdal galaxies with a $r^{1/4}$ profile the fit would return a value $N \sim 0.25$. Bulges are expected to follow a $r^{1/4}$ profile and their presence in disks results in $N < 1$. Thus, the $N = 1$ galaxies in Fig. 2 are expected not to contain any significant bulge, which

[2] radius from within half of the total light is originating

Figure 1. The various steps involved in opacity studies

Figure 2. The surface brightness inclination test, at the effective radii of pure exponential disk galaxies. *Left:* Sb's, *right:* late type spirals (Sd's). The curves represent expected trends for simple absorption models (transparent C=1, semi-transparent C=0.5). The hobbling line represents the observed running average.

could possibly pollute the inclination test. The constancy of the local surface brightness at the effective radius of Sb galaxies for various inclination angles, as is clear in Fig. 2, can directly be taken as a signature of optically thick galactic disks.

For comparison, Fig. 2 presents a similar plot for late type spiral galaxies (type $\geq$ 7.0, Sd and later). This graph shows a significant increase of surface brightness with inclination, demonstrating, in the first place, that the inclination test is capable to trace this effect and that late type spirals behave rather different when compared to earlier type (Sb-c) spirals. A detailed map of regressions, C, as function of galaxy type and central surface brightness (the second critical parameter which determines the opacity of spirals) is given in V90 and V94.

The problems with various sample/parameter combinations, the second step on the ladder, have been extensively discussed elsewhere (Burstein *et al.* 1991, V94). Burstein *et al.* rightfully warn against combinations in which both distant dependent *parameters*, such as the apparent diameter or the apparent magnitude, and distant dependent *selection criteria* are used. However, these objections do not relate to the V90 results, for which the, distant independent, local surface brightness was used as the parameter. This is further illustrated in V94, in which for a variety of sample selections, the same result is obtained: a very modest inclination dependency of the local surface brightness of Sb and Sc galaxies, at least at their effective radius.

When redshifts of the samples are known, a number of distant dependent selection effects can be circumvented. By applying Tully-Fisher type of relations the intrinsic magnitudes or diameters can be predicted, which can be compared with observed, inclined, magnitudes or diameters. Burstein *et al.* (1991) claim that such an analysis leads to an optical thick result, which view is however revised by Burstein's presentation at this conference. Gouguenheim *et al.* (this conference and Bottinelli *et al.*, 1994) apply the same technique and conclude that isophotal diameters are not inclination dependent, as expected in the optical thick case.
It is important to note, that also redshift selected samples can be subject to biases. Gouguenheim *et al.* circumvented these biases by selecting galaxies from the 'plateau' in the diagram of the Hubble constant versus the kinematic distance. This way, an unbiased TF relation is obtained from an unbiased sample. At this point, it is not clear whether such precautions were undertaken in Burstein's recent result.

In V90, the opacity at the outer regions was studied by evaluating the distant independent ratio of the photometric diameters D_{26}/D_e. The absence of an inclination dependency of this ratio was interpreted as evidence of a similar opacity at both locations.

Another way to assess distance dependent selection effects is to compute V/V_{max} values of the sample, while varying the cutoff limit of the sample. This way, V94 demonstrated that incomplete samples, with $V/V_{max} < 0.5$, exhibit an increase of isophotal diameters with increasing inclination angle, a property of transparent outer regions. On the other hand, complete samples with $V/V_{max} = 0.5$, which have been cut at a higher limit, do not show any significant increase of isophotal diameters with inclination angle (see Fig. 3).

The issue of the opacity of spiral disks is most important in the regions at and beyond the effective radii of the disks. When a value of the optical depth around unity would be deduced in these regions, then this will have important consequences for several astrophysical issues. A face-on optical depth around unity is generally believed to result into the absence of a diameter increase with inclination, but transparent disks would lead to a significant diameter increase. Fig. 3 show that no diameter increase is

Figure 3. The apparent isophotal diameter increase (D_{26}^{oct}, between a/b=1 - nearly face-on- and a/b=5 - nearly edge-on-) versus V/V_{max} values. Complete samples with $V/V_{max} \sim 0.5$ do not show a significant diameter increase.

observed in unbiased samples, a result which agrees with earlier V90 results, with that of Gouguenheim *et al.* and with Choloniewski (1990), but not with Burstein's presentation given at this conference.

Huizinga and van Albada (1992, see also Huizinga's thesis, 1994) deduce transparent outer regions by assuming that the original visual diameter estimate of Lauberts (D_{org}) are incorrect and that the ESO-LV value of the diameter at the 26^{th} isophote (D_{26}) are correct, in spite of the notion by the authors of the ESO-LV catalogue that, due to a technicality, an artificial inclination dependency was introduced in the D_{26} listed in ESO-LV [3].

V94 announces a recipe for a small correction to D_{26} leading to D_{26oct} which uses the computerized determinations of axial ratios (a/b_{oct}) rather

[3] D_{org} = visual, UGC, Lauberts eye, ESO-Uppsala
D_{26} = ESO-LV, computerized using $(a/b)_{org}$, obtained visually
D_{26oct} = ESO-LV, computerized using $(a/b)_{oct}$ (also computerized)

than the visual estimates of a/b. This recipe is confirmed photometrically by Peletier *et al.* (1994b) and numerically by Rönback and Bergvall (1994). The validity of using the octant axial ratios for computing diameters, rather than the original visual axial ratios is also evident from a graph which is presented by Huizinga. When comparing with Buyn's axial ratios, the dispersion of ESO-LV's (a/b_{oct}) is much smaller than that of $(a/b)_{org}$.

After applying this recipe, the corrected ESO-LV D_{26oct} values are in a very good agreement with the original visual estimates for all inclinations. Both diameters do not show any significant correlation with inclination and thus conform the expectations for optically thick outer regions. Unfortunately, the conclusions of Huizinga and van Albada are caused by neither using the original visual diameters, nor the corrected ESO-LV values.

I conclude, that current studies still strongly suggest the absence of a diameter increase with inclination in the B band of Sb, Sbc galaxies.

2.2. MODELS VERSUS DATA

The regression coefficient C of the observed local surface brightness versus 2.5 $\log(a/b)$ has often been used to interface observed trends to predictions from detailed models. Analytical solutions for the absorption in disks with various layers of homogeneously distributed stars and dust are pretty straightforward and provide in general a good first order guideline for the interpretation of observational data, like C. However, both the effects of scatterings and inhomogeneous dust distributions are complicated and have to be taken into account. Good progress on the modeling side has been reported at this conference (*e.g.* Bruzual, Buyn, Kylafis, Witt). Particularly, Witt's (also Witt *et al.* 1992) results on brightening of face-on galaxies and possible de-reddening (bluing) should be taken as a warning against the over-interpretation of simple models. On the other hand, many of the basic notions of simple multiple layer absorption models are reproduced in the more advanced evaluations of the radiation transfer problem.

For a simple slab model with a homogeneous mix of stars and absorbers, or for a sandwich model with transparent outer layers, the regressions (values of C) reported in V90 and V94 correspond to optical depth listed in Table 1. The observed absence of an increase of isophotal diameters corresponds in these models to an optical depth around unity at the outer radii. As outlined in V90, the tabulated radial variation of τ is approximately a factor 10 less than the radial variation of the emitted star light. Thus, the data suggest an absorbing component with an exponential scale length larger than that of the stars (this was actual the motivation for the alternative two-disk rotation curve solutions, GV91).

Note, that at this state of the process (fourth box on the ladder, Fig. 1)

TABLE 1. Very global face-on B band optical depths of Sb galaxies

Center:	C $\sim$ 0	$\tau \sim$ 5-30
effective radius:	C $\sim$ .2	$\tau \sim$ 1-2
D_{25},D_{26}:	C $\sim$ .2-.4	$\tau \sim$ 1

we need not yet to define the nature of the absorbers, they are only assumed to be well mixed with the stars. The next step involves the identification of the nature of the absorbing bodies. With this I mean, that several models allow to *a postiori* discriminate between the relative contributions of compact opaque clouds and cirrus-type of dust grains. Fundamentally, a measured value of τ relates to value of the product of the disk geometrical thickness, the obscurers cross sections and their spatial density ($T\sigma\rho_0$). This propagates to a total mass of absorbers in the disk, $M_{disk} \sim \tau(m/\sigma)R^2$, with m the mass per absorbing body and R the disk radius. Obviously, for solid bodies $m/\sigma \sim r$, with r the radius of the body. Then, a value of $\tau \sim 1$ immediately rules out any significant contribution to the opacity of disks by means of solid bodies with radii larger than a fraction of a micrometer, thus, for example, excluding asteroïds, planets etc., as these will lead to unacceptable total disk masses. However, virialized clouds have the property m/σ independent of r and thus they can contribute significantly to the opacity without trespassing total disk masses. In the models, compact clouds can be taken as black balls, optically thick at the shorter wavelength, which act as pure absorbers without scattering. In this way, I originally introduced molecular clouds in the simple models and identified them as possible candidates for the obscuring component with a scalelength larger than that of the stars. It is noteworthy, that Witt's findings on the effect of clumpiness of the interstellar medium in fact corresponds closely to what one would expect from the 'black ball' models. He reports:

- in clouds scattering can be ignored,
- absorption is relatively independent of cloud structure
- transparency goes up with clumpiness
- extinction is grey, once clumps are optically thick.

3. (Near) Infrared studies

An absorbing component which extends to the outer regions of disks influences the exponential radial scalelength in the passbands that are affected by the absorption. As the near-infrared K passband is believed to be hardly affected, a scalelength observed at K would closely correspond to that of the intrinsic stellar distribution. Thus, a comparison of scalelength at short wavelength with that at the K band will provide valuable information on the radial distribution of the absorbers, when the effect of radial population gradients (colour gradients) can be controlled. For this reason, Peletier *et al.* have mapped at K a representative sample of 38 Sbc galaxies and compared the observed scalelength ratios in B and K to models with dust radial scalelength as a free parameter (Peletier *et al.*1994a,b and this Volume). They find the scalelength ratio (B/K) in the range 1.3-1.9, with a trend for that ratio to increase with inclination angle. Analytical solutions of a radial version of the equation of radiation transfer were made for a variety of dust spatial distributions. In its most simple form, the model predicts a relation between central optical depth at the observed passband (*e.g.* B band), the scalelength at the observed wavelength, α_{obs}, the scalelength of the dust component (α_d), the intrinsic scalelength of the stars ($\alpha_\star$, as mapped at the K band images if colour terms in stellar populations can be handled) of the form:

$$1 = \frac{\alpha_{obs}}{\alpha_\star} - \frac{\alpha_{obs}}{\alpha_d} - 0.5\, ln\, \frac{(1 - e^{(-\tau_0\, exp(-3\alpha_{obs}/\alpha_d))})}{(1 - e^{(-\tau_0\, exp(-\alpha_{obs}/\alpha_d))})},$$

when the scalelength fits are made in the radial range between 1 and 3 scalelength. τ_0 is the central opacity in the observed pass band, $\tau(r) = \tau_0$ $\mathrm{e}^{(-r/\alpha_\mathrm{d})}$.

Thus, a particular observed B/K scalelength ratio ($\frac{\alpha_{obs}}{\alpha_\star}$) corresponds to a set of solutions of τ_0 and α_d. We find that observed B/K values can not be satisfactorily reproduced with this model when we require $\alpha_d = \alpha_\star$ and an optical depth in the B band at the outer radii of about 1, as suggested by the inclination tests summarized in the previous Section. But, acceptable solutions are found when the requirement of semi-transparent outer regions is dropped, which solutions, however, do not reproduce the observed trend in the B/K scalelength ratio inclination test.

Again, this implies that we have to consider models in which at least one dust component has a scalelength larger than that of the stars. Two-component models were considered: one dust component with a scalelength following that of the stars, the other component with a larger scalelength. We evaluated such models with various scaleheights of the dust distribution, compared to that of the stars. A reasonable description of all available observational data can be made when the first component, which follows the radial distribution of the stars, has a central optical depth in the range 0.6 - 3.0 and is fully transparent at the outer regions, while the second component has a scalelength in the range 2-4 times that of the stars, and an optical depth around unity at the outer radii (see Table 3).

The dust component that follows the stars, is nearly transparent at the effective radius and its spatial distribution matches to the dust as detected by IRAS. It can, most likely, be associated with the warm dust as seen by IRAS.
Conversely, the second component, with a scalelength larger than that of the stars, could be associated with a much cooler dust component $< 20K$, such as molecular clouds and would not have been detected by IRAS.

Van Driel *et al.*(1994 and this Volume) report on a similar type of scalelength ratio study, but now involving the FIR bands at 50 and 100 μm. The mean observed scalelength ratios $\alpha_{100\mu m}/\alpha_{50\mu m}$=1.21 and $\alpha_{\rm B}/\alpha_{100\mu m}$=1.12 are most difficult to describe with single component dust models, especially when the B/K scalelength ratios as observed by Peletier *et al.* would also apply to van Driel *et al.*'s sample. Accordingly, van Driel *et al.* conclude that multiple component dust models, such as suggested above, are required to understand the FIR data.

4. Concluding Remarks [4]

I have been asked to compare the V90, V94 results with presentations given at this conference. My main conclusion is: 'that the modern literature is considerably less controversial than is often stated, but that opacity studies of the outer regions of Sb and high surface brightness Sc galaxies require an absorbing component with an exponential scalelength which is larger than that of the stars'.

On Tuesday afternoon we had a discussion session during which we compared the results of several studies. When comparing these with my 1990,1994 results, it appears that there is a **reasonable agreement** about the following items:

•< 1989 studies needed a critical review in the light of more recent results.

In many presentations substantial column densities of dust were reported.
Different views on the overall optical thickness of spiral disks were well presented at this conference, but actually, it was interesting to hear that Bosma and Freeman, who arrive at the lowest optical depth values after analysing rotational velocities of edge-on galaxies, acknowledged that they had to put there slit next to the dust lane, otherwise they 'could equally well go observing the night sky'.

•Relatively high optical depth ($\tau^B_{face\_on}$) in the centers of spirals (3-10),

e.g. Pravda's steepening of rotation curves with wavelength
e.g. Peletier's almost 2 times larger dispersion of the central surface

[4]Summary of Panel presentation, given at the conference review session

brightness in K compared to that in the Blue band.
e.g. Peletier's high B/K scale length ratios.

- A $\tau^B_{face\_on} \sim 1$ at the effective radius (1.7 scalelength) in many Sb,Sbc's
- The variation of optical depth along morphological type:

  low for early types, higher for types 3-5 and again lower for the later types (e.g. Table 2).
  Also Bosma listed this variation, but perhaps with a smaller amplitude.
- IRAS seen dust does not account for high optical thickness.
- Cold, $T_{dust} < 20$ K, dust is very important.
- Galaxies are nearly transparent at the K-band.

Table 2 contains a compressed summary of my results, when observed trends are transformed to face-on optical depth by means of a sandwich model, ignoring the effects of various types of scatterings.

TABLE 2. Global values of the optical depth at various positions

Galaxy type			τ^B_{face} values		
type	type	central sb	center	D_{eff}	$D_{25} - D_{26}$
Sa	0-2.5	all (20.5)	<0.5	<0.4	<0.4
Sb,Sbc	3-5	all (21.0)	>3	1	1 *
Scd	5.5-6.5	21.0-21.5	>2	.7	.6 *
		21.5-22.0	1	.4	.2
Sd	7-9	>22.0	.5	.2	.1

Most values are in reasonable agreement with the conference results with the exception of the two values marked with *, which correspond to the optical depth around unity in the outer regions of Sb, Sbc and high surface brightness Sc galaxies. On this issue there is **no uniformity** of results. This is an important issue, as it relates to about 50% of the spiral galaxies as seen by the ESO-LV survey. Note also, that the regions beyond the effective radii contain by definition half of the observed total light.

Table 3 lists the basic properties of my currently favorite model that results in an optical depth around unity at the outer regions. This is a two component dust model with one component following the scalelength of that of the stars, the other one having a larger scalelength.

This model is consistent with and has been discussed here by:
- the V90,V94 results,

TABLE 3. Range of parameters of acceptable two-component models

		range of τ^B_{face} values		
	$\alpha_{dust}/\alpha_\star$	center	D_{eff}	D_{25}
first component :	1	0.6 - 3.0	0.1 - 0.3	0 - 0.05
second component :	3-4	4 - 2	2 - 1	1 - 0.8

- the B/K scalelength ratios presented by Peletier *et al.*.
- the FIR/optical/K scalelength ratios presented by van Driel.

Unfortunately, none of the other detailed model calculations presented at this conference compute dust configurations with scalelengths larger than that of the stars (or models which show no increase of diameters with inclination) and the above table remains a challenge to 'the model makers'. Models including scattering and clumpiness might help to solve the problem of the opacity in the outer regions.

The issue of the opacity at the outer regions is important as it relates directly to two important astrophysical items:
- what is the nature of the absorbing regions that contribute to the optical depth: cold dust, molecular clouds?
- the basic rationale of the maximum disk analysis (which let us believe that we are forced to consider dark haloes to solve flat rotation curves) does not apply when a dust component with a scalelength larger than that of the stars exists. Silk's proposal at this conference for a large number of compact molecular clouds in the halo might be related to this issue, but I still prefer a geometry with compact clouds in the disk.

TABLE 4. The controversy of inclination test results at the outer regions.

Diameter increase ($a/b = 1 -> a/b = 5$):	< 1.1	$\sim$1.4
τ^B_{face} at D_{26}:	~ 1	<.2
Tully-Fisher technique:	Gouguenheim	Burstein
direct diameter-inclination test:	V94	Huizinga
D_{26}/D_{eff} ratio technique:	V90	

Papers relating to the opacity at the outer regions, as presented at this conference, are categorized in Table 4. In a perhaps slightly oversimplified way these papers can be divided into two groups: those who report on the absence of a diameter increase with inclination and a corresponding relatively high optical depth (column 2) and those who report on a significant diameter increase and a low optical depth (column 3).

Gouguenheim et al. demonstrated possible selections effects also in the T-F tests, and they have carefully avoided these by selecting objects from the 'plateau' of their diagram. Such precautions were not evident in Burstein's presentation. An easy verification would be to run the V/V_{max} test both on Burstein's sample and on Gouguenheim's sample.

The differences between Huizinga's and my 1994 result are caused by a technicality as explained in Section 2.1, which I believe is resolved by a small update of ESO-LV parameters, as proposed in V94.

I think it is great we have achieved so much understanding at this conference, and a rather surprising agreement about quite a number of issues, but the remaining issues will keep this field alive for some time to come.

References

1. Bosma A., Byun Y., Freeman F.C., Athanassoula E., 1992, ApJ 400, L21
2. Bothun G.D., Rogers C., 1992, AJ 103, 1484
3. Bottinelli L., Gouguenheim L., Paturel G., and Teerikorpi, P., 1994, *A&A* in press
4. Bruzual G.A., Magris G.C., Calvet N., 1988, ApJ 333, 673
5. Burstein D., Haynes M.P, Faber S.M., 1991, Nature 353, 515
6. Buyn Y.I., Freeman K.C., 1991, Proc. ASA 9, 86
7. Choloniewski J., 1991, MNRAS 250, 486
8. Disney M., Davies J.I., Phillipps S., 1989, MNRAS 239, 939
9. González-Serrano J.I., Valentijn E.A., 1991, (=GV91) Peletier, R.F., A&A 242, 334
10. Huizinga J.E., van Albada T.S., 1992, MNRAS 254, 677
11. Huizinga, J.E., 1994, Ph.D Thesis, University Groningen
12. Lauberts A., Valentijn E.A., 1989, The Surface Photometry Catalogue of the ESO-Uppsala Galaxies (= ESO-LV), ESO, München
13. Peletier, R.F., Valentijn, E.A., Moorwood, A.F.M. and Freudling, W. 1994a, A&A Suppl., 108, 621
14. Peletier, R.F., *et al.* 1994b, A&A (Letters), submitted
15. Rönnback J., Bergvall, N., 1994, A&A Suppl., 108, 193
16. Valentijn E.A., 1990, (= V90) Nature 346, 153
17. Valentijn E.A., 1991a, (= V91) Proc. IAU Symp. No 144, ed. H.Bloemen, Kluwer, p 245
18. Valentijn E.A., 1991b, ESO Messenger 63, 45
19. Valentijn E.A., 1994, (=V94) MNRAS 266, 614
20. van Driel, W., Valentijn, E.A., Kussendrager, D. and Wesselius, P.R., 1994, *A&A (Letters)*, submitted
21. Witt A.N., Thronson, H.A., Capuano, J.M., 1992, ApJ 393, 611