The opacity of spiral galaxy disks.
Holwerda, Benne

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Discussion and Outlook

Distant galaxies have been observed through the disk of a foreground spiral galaxy for quite some time. These observations have now progressed from mere anecdotal evidence of disk transparency to a valid, calibrated and well-understood method to quantify the dust content of the disk.

The intuitive conclusion that the disk is effectively transparent - because one can see a distant object through it - has conclusively been proven too naive. In the case where one can observe such an object, the disk is likely more transparent. Such observations can be made surprisingly close to the center of a spiral galaxy. This is, however, only part of the picture. Some of the distant galaxies are obscured and their absence is much more telling. The potential for using the number of distant galaxies in a field as an extinction probe was recognized very early in the research into spiral galaxies but could only be used qualitatively (§ 1.7.2). Calibrated counts can give a quantitative answer.

My conclusions are listed at the end of each of the preceding Chapters but the main conclusions are summarized below. How the results compare to earlier work, their implications and still outstanding questions are also discussed.

9.1 Results from this thesis

The crucial contribution by González et al. (1998) was to introduce the “Synthetic Field Method”. This method calibrates the number of distant galaxies for the effects of the many foreground objects, making this number a quantitative measure of dust extinction. This first paper proved the SFM technique to be feasible. In addition it became clear that this method required high-resolution space-based HST imaging and that much more solid angle needed to be analysed.

The first step in the thesis project was to automate the technique (Chapter 2) in preparation for its application to a much larger set of HST images. These were subsequently selected from the archive (§ 3.2) and processed (§ 2.3.1).
The initial application of the automated method, again to NGC 4536, offered results very similar to those of González et al. (1998). This outcome was encouraging, for it shows that the results obtained are independent of the ‘observer’, who does the actual object classification (§ 2.5.1). While the identification process is not completely automated as yet, the independence of observer does show that the method could, in principle, be fully automated provided the same identification criteria are applied to both synthetic and science fields. In the process of automation the uncertainty estimate, as well as the standard reference field were improved (§ 2.4.3).

The automated method allows for a uniform analysis of many fields, the original goal of this thesis project. The general values of disk opacity from the combined counts could now be compared to other disk characteristics. The first results by González et al. (1998) were presented per chip of the WFPC2 array. An approach that could reveal more about the spiral disks is to group the counts of distant galaxies according to some characteristic of the foreground disk. The pilot results are presented in Chapter 2. The foreground disk characteristics used are:

1. Projected radius from the center of the foreground galaxy (Chapter 3),
2. Near infrared surface brightness of the foreground disk (Chapter 5) and
3. Typical region in the spiral galaxy, e.g. arm or disk (Chapter 3).

The radial profiles of extinction can subsequently be compared to existing profiles in the literature, such as the atomic hydrogen surface density (Chapter 4), the SCUBA sub-millimeter emission profile (Chapter 4) or the Spitzer mid-infrared emission profile (Chapter 6).

The radial extinction profiles based on the number of distant galaxies seen through a disk, indicate that significant absorption occurs for most of the optical disk (Chapter 3, Figure 3.2). The inner part of a spiral disk is shown to be a lot more opaque than the rest of the disk where the extinction remains nearly constant out to the $R_{25}$. Spiral arms do have an effect on this radial profile (§ 3.5.2, Figure 3.7). These display a higher opacity and a stronger radial dependence of extinction in comparison to the rest of the disk.

The opacity is a measurement through the whole height of the disk, a value not directly probed in other studies except for the overlapping pairs of galaxies analysed by the Keel and White group (§ 1.7.1). It is especially encouraging to see that both techniques agree very well, despite the completely different assumptions, strengths and weaknesses (Chapter 3, Figures 3.9 and 3.11).

The fact that this opacity measurement appears to be independent of the inclinations of the disks, indicates that the dust responsible is not distributed uniformly but in a patchy and flat distribution. The filling factor of the clouds is the prime factor in our measurement (§ 3.5.1). By comparing the average colors of the distant galaxies found as a function of radius and therefore opacity, it becomes clear that the distant galaxies do not appear reddened (Figures 3.14 and 3.15 and § 3.6). This can also be interpreted as an effect of a patchy distribution of dust. A short discussion on the effects of a clumpy distribution of dust on counts of synthetic galaxies is presented in Appendix C. The effects of a clumpy dust distribution on counts of distant galaxies is a line of future inquiry.

The radial dependences of opacity and average surface brightness appear to be somewhat correlated (§ 3.7, Figure 3.16). Such an interdependence would indicate that the dark dust
clouds are spatially correlated with the stellar distribution. A higher surface brightness does, however, limit the accuracy of the SFM (Chapter 7, Figure 7.2), although a measurement is still feasible.

A better understanding of the relation between dust extinction and surface brightness can be found when the counts of galaxies are directly compared per surface brightness value. There is a relation between surface brightness and opacity for the brighter parts of the disk (§ 5.4), mainly the spiral arms. This observation is consistent with the notion that the arms are overdensities in the disk (§ 5.5). Over the rest of the disk, however, the opacity remains relatively constant with surface brightness. This effect is another aspect of the flat radial extinction profile of the disk outside the spiral arms.

The radial profiles of HI and opacity can also be compared. In the case of individual galaxies, there seems to be no relation—not surprising given the prevalent profiles in HI with a central dip and the peak in the disk whereas opacity profile rises towards the center (Figure 4.1a, § 4.3). When the counts of the galaxies and the HI profiles are averaged, the ratio between dust and HI is higher than found in previous studies (Figure 4.3, § 4.4). One could argue that the SFM, which is independent of dust temperature, detects all the dust in the disk. A large part of this dust may be hidden in dark cold clouds. In future applications of the SFM, the counts of distant galaxies can be compared directly per contour of HI column density, similar to the sorting by surface brightness done in Chapter 5. Any relation found by this comparison would be more robust.

Sub-millimeter emission is much more sensitive to colder dust in the disks of spiral galaxies. Unfortunately, the SCUBA instrument has not mapped many galaxies in this thesis’s sample. In the few cases it did (Chapter 4, § 4.5) the radial profile of opacity and sub-mm emission could be similar. Much better comparisons can be made for future SFM counts and sub-mm maps. The Spitzer Space Telescope has mapped many more galaxies in this thesis’s sample but it observes at shorter wavelengths. In order to match up the emission profile at 160 micron and our opacity measurements, a low (single) temperature of the dust needs to be assumed for the conversion from flux to optical depth (Chapter 6). A more realistic approach should contain a dust temperature gradient with radius as a result of the diminished heating by stars at greater radii.

Generally speaking, we can conclude that the dust extinction in a disk does not follow either the stars or the atomic gas completely but remains somewhere in between. One could speculate that the dust recently produced by stars still follows the stellar distribution, while some other fraction was ejected or produced earlier and therefore extends to higher radii.

How the calibration of the counts depends on foreground disk characteristics could be explored using the dataset analysed here with the SFM. The SFM’s accuracy can be shown to depend on surface brightness and the normalization on granularity of the field (Chapter 7). These relations could in principle be used to obtain an opacity estimate, foregoing synthetic fields completely.

The optimal distance of the foreground disk for SFM analysis is between 5 and 35 Mpc. The field becomes too grainy to find enough distant galaxies in nearby disks\(^1\) and the disk

\(^1\)The WFPC2 fields of the closer M51 and M81 are somewhat more grainy than the rest of the sample. See
does not cover enough distant galaxies -i.e. solid angle- if it is too far away.

A more realistic model of dust in a spiral disk is a clumpy distribution of dark clouds. How the number of distant galaxies depends on a given clumpy dust distribution can best be explored using a large dataset on a single spiral disk.

In future use of the counts of distant galaxies as an extinction probe, synthetic fields will probably remain necessary, given the unique circumstances in each foreground field. It is very possible, however, that the detection and identification of objects in these fields may become completely automated.

There are many fields in the Hubble archive, notably those made with the ACS, that can be analysed to answer some of the outstanding questions on the extent and character of dust in spiral disks.

### 9.2 Comparison of results with earlier work

Calzetti (2001) reviews the current consensus on the opacity of disks. The consensus has arrived at the following conclusions: the central regions of disks are opaque while the outer regions (beyond 2-3 scalelengths) are almost completely transparent (Huizinga and van Albada 1992; Huizinga 1994; Peletier and Willner 1992; Giovanelli et al. 1994, 1995; Jones et al. 1996; Moriondo et al. 1998; Masters et al. 2003). The face-on opacity in the outer parts of the disk should be about 0.25 magnitude in the I-band (Peletier and Willner 1992). The scale lengths of the dust is about 40% more than the scalelength of the stars (Xilouris et al. 1999). Spiral arms are more opaque than the surrounding disk (Beckman et al. 1996; White et al. 2000) and the brighter galaxies have in general more opaque disks (Giovanelli et al. 1995; Masters et al. 2003).

The results from the counts of distant background galaxies, presented in this thesis, agree with some of these earlier studies very well. However, the radial plot in Figure 3.2 seems at first hard to reconcile with some results from other authors. The extinction found in the optical disk is indeed more than the 0.25 mag but several factors should be considered here. First, the results in Chapter 3 were not corrected for inclination, because dust geometry is itself a factor in the inclination correction of extinction measurements. On the other hand, in general inclination studies use a simple slab model so their correction to face-on values also suffers from this problem. The other methods mostly use the disk’s own light to probe extinction and therefore become less accurate in the low surface brightness part of the disk. In contrast, this thesis’s results improve for low surface brightness of the foreground disk. And our method measures the opacity due to the entire height of the disk of a spiral galaxy. Therefore, the higher values of opacity at the $R_{25}$ seem realistic.

In addition, counts of galaxies show that the spiral arms are more opaque than the disk. Again the occulting galaxy technique agrees very well with this result (White et al. 2000), as do models of the surface photometry of disks (Beckman et al. 1996). The spiral arms show a gradient of opacity with radius as well as with surface brightness, while for the rest of the disk the opacity is more constant with both radius and surface brightness. This is consistent

Appendix A.29, A.30 and A.10.
with e.g. the SCUBA map of M51 by Meijerink et al. (2005).

The opacity profiles in early (Sab-Sbc) and late type spirals (Sc-Sd) also agree with earlier results (Peletier et al. 1995). The later types appear to be almost transparent at the $R_{25}$ while the earlier types show more opacity at that radius.

The average color of the galaxies does not indicate any reddening. González et al. (1998) point out that the SFM cannot distinguish easily between a Galactic or a grey extinction law. The interpretation for this is that the distant galaxies found are inherently on a lower-opacity line-of-sight. That is, the missing galaxies are dropped from the selection by fully opaque clouds. For comparison, the occulting galaxy technique finds also an extinction law greyer than the Galactic one in the initial results (White et al. 2000). However, they find reddening consistent with the Galactic Extinction Law in HST observations (Keel and White 2001a,b), provided the linear resolution is better than 100 pc. Since the SFM measures an average extinction over an area of a foreground disk which corresponds to a section larger than 100 pc, the grey extinction result is very much in agreement with the Keel and White findings.

A well-behaved extinction law for our distant galaxies would have been a suspicious result. The distant galaxies are extended sources with large color spread. And these have been found on probable low-opacity lines of sight. The opacity was derived from the absence of their colleagues. Therefore the major part of the light from which the reddening is determined suffers from little extinction. An extinction law would have implied an extremely smooth, uniform and diffuse dust screen in all our disks, a highly unlikely scenario.

The brighter regions in the images -center and spiral arms- do show more extinction derived from galaxy counts. This is similar to the global relation found by Giovanelli et al. (1995); Tully et al. (1998); Masters et al. (2003) that brighter galaxies are also more opaque. The constant opacity for the dimmer parts of the disk (Chapter 5) is consistent with the more extended dust disk found in Chapter 3 and sub-mm observations of extended dust disks by several authors.

The flat radial distribution of the dust is also the reason that dust scalelengths are found to be much larger than in previous measurements (Figure 5.9), such as the value of 1.4 times the disk’s scalelength, that Xilouris et al. (1999); Radovich et al. (2001) find for edge-on galaxies. Cold dust disks were found by several authors to be more extended than the optical disk (Nelson et al. 1998; Alton et al. 1998b; Trewhella et al. 2000) but the actual extent of the dust disk is still unknown. Future opacity measurements from counts of galaxies and sub-mm observations should resolve the extent of this cold dust disk.

9.3 Implications of the results

There are several implications from the results in this thesis. The picture of dust in the disks of spiral galaxies that emerges has consequences for both our observations of the old and distant Universe as well as our view of spiral disks.
9.3.1 Implications for our view of spiral galaxy disks

The initial assumption that dust follows an exponential disk, similar to the stellar light may be too simple. There is an additional extended dust distribution in the disk, seen in the SFM opacity estimates and sub-mm observations. Its actual extent is still unknown but it appears to be larger than the optical disk and smaller than the HI disk. Models of the evolution of spiral galaxies need to explain how this dust got there. Did it form at these radii? Did galactic fountains bring it there? If there are dark cold clouds at larger radii, as the results suggest, is there some star-formation associated with it?

The relation between light and opacity for the brighter regions implies that some of the dust, however, does follow the distribution of stellar light. This implies that some of the stellar mass in the disk is still hidden, especially in the central part of the disk. A constant mass to light ratio - often assumed for the stellar disk - does not take this extra component in the brighter regions into account. The fact that the brighter spiral arms are more opaque than the rest of the disk implies likewise that these are more dense than the rest of the disk.

Dust in our own Milky Way is concentrated in dense clouds. This clumpiness is also evident from the counts and colors of distant galaxies in other disks. A grey opacity of 1 magnitude implies a filling factor of about 60%. If these clumps are of the same angular scale as the background galaxies, one could imagine that this observed filling factor is an upper limit. It is easily conceivable that a dust cloud does not need to cover the entire background galaxy to cause it to drop from the selection. However, synthetic fields using large clouds show a much shallower relation between number of background galaxies and opacity (See Appendix C). The inferred opacities would have been much higher using clumpy simulations. The agreement between the SFM opacity values and those from occulting galaxies argues against a predominance of these cloud sizes. Numerous very small clouds have the same effect on the number of distant background galaxies as the smooth screen. Their angular size would have to be of the order of one pixel, a linear size approximately 1-10 pc. This is a typical scale of the dark cores in our own Galaxy. The relation between distant galaxy numbers and a distribution of cloud sizes can be explored much better in a single disk at one distance.

The clumps are very cold for the most part. The infrared emission comes from the sides of these clouds which are heated by stellar radiation. Not surprisingly, the colder parts of the clouds become a bigger fraction of the dust at higher radii, as the stellar radiation field drops off.

The gas and dust in these cold clouds, in a radial distribution that differs from both the HI and the stellar component, should play some role in the dynamical model of spiral disks. It probably will not explain the dark matter contribution completely but its role should be quantified and explained, at least before more esoteric forms of baryonic matter are invoked. The best quantification of this component would be improved sub-mm observations. Counts of galaxies can verify the surface densities found by these observations independently. Especially to verify the assumed emissivity of the dust grains at sub-mm wavelengths.
9.3.2 Implication for observations of the high-redshift Universe

The more distant Universe, e.g. the number of distant galaxies, is the background source used in this thesis to measure disk opacity, but the disk opacities found here have implications for our view of the distant universe as well.

Several papers model the cumulative effects of extended dust disks of foreground galaxies on our view of the higher redshift Universe, especially their effects on distant Quasi-Stellar Objects (QSO)\(^2\). Many of these distant QSO’s were found from radio and gamma-ray surveys, while their optical counterparts were faint and reddened. Therefore, most of these papers parameterize the dust disk of spirals as an exponential disk of diffuse dust, sometimes one that evolves with time (Masci and Webster 1999). However, if the dust is more in a flat and clumpy distribution, the effects on QSO populations are likely to be different from the ones in these models. The flat distribution means that the effects can be more severe, at least those caused by the nearby galaxies. The assumed evolution of the dust disk in the models would also have to explain the observed distribution of dust in the disks. A clumpy nature of the dust clouds would not result in as much reddening as a smooth screen and would also not result in a covering fraction as high as found these models (see e.g. Alton et al. (2001a)). However, the true structure, composition and full extent of the dust beyond the optical disk remains mostly unknown. Therefore, more observations in emission as well as from counts of distant galaxies are needed.

9.4 Questions remaining...

This thesis sought to address some questions on the opacity of spiral disks e.g. how much is it? Does it scale with the light? Does it hide much of the disk we see? What is its relation to atomic hydrogen? Do different Hubble types have more dust than others? These questions have been confronted in the previous Chapters to the degree data and method allowed.

Naturally more and new questions remain. At what radius is there no more extinction? What is the relation with HI column density on smaller scales? Is the opacity due to the sub-mm cold dust disk that some authors find? What does a comparison between infrared emission and opacity tell us of the dust temperature gradient in a disk or even its composition?

Counts of galaxies have been used to address the problem of the opacity of spiral galaxies in the past and with more data already in the archives and still outstanding questions, they will surely be used in the future.

\(^2\)See Ostriker and Heisler (1984), Heisler and Ostriker (1988), Masci and Webster (1995), Masci and Webster (1999) and Alton et al. (2001a) for the effects on the high-redshift Universe.