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## Structure and Evolution of the Opacity of Spiral Disks

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**Abstract.** The opacity of a spiral disk due to dust absorption influences every measurement we make of it in the UV and optical. Two separate techniques directly measure the total absorption by dust in the disk: calibrated distant galaxy counts and overlapping galaxy pairs. The main results from both so far are a semi-transparent disk with more opaque arms, and a relation between surface brightness and disk opacity. In the *Spitzer* era, SED models of spiral disks add a new perspective on the role of dust in spiral disks. Combined with the overall opacity from galaxy counts, they yield a typical optical depth of the dusty ISM clouds: 0.4 that implies a size of  $\sim 60$  pc. Work on galaxy counts is currently ongoing on the ACS fields of M51, M101 and M81. Occulting galaxies offer the possibility of probing the history of disk opacity from higher redshift pairs. Evolution in disk opacity could influence distance measurements (SN1a, Tully-Fisher relation). Here, we present first results from spectroscopically selected occulting pairs in the SDSS. The redshift range for this sample is limited, but does offer a first insight into disk opacity evolution as well as a reference for higher redshift measurements. Spiral disk opacity has not undergone significant evolution since  $z=0.2$ . HST imaging would help disentangle the effects of spiral arms in these pairs. Many more mixed-morphology types are being identified in SDSS by the GalaxyZoo project. The occulting galaxy technique can be pushed to a redshift of 1 using many pairs identified in the imaging campaigns with HST (DEEP2, GEMS, GOODS, COSMOS).

The opacity of spiral disks is a characteristic that influences many of our observations of disks at any redshift. Thus far, two observational methods have produced reliable measurements of disk opacity; occulting galaxy pairs and the calibrated number of more distant galaxies. Together with *Spitzer* SED models, the apparent optical depth can be used to estimate general properties of the extinguishing ISM 's structure.

### 1. Distant Galaxy Counts

The number of distant galaxies seen in an *HST* image through the face-on foreground spiral is a direct indication of its opacity, after proper calibration using artificial galaxy counts (the “Synthetic Field Method”, SFM, González et al.

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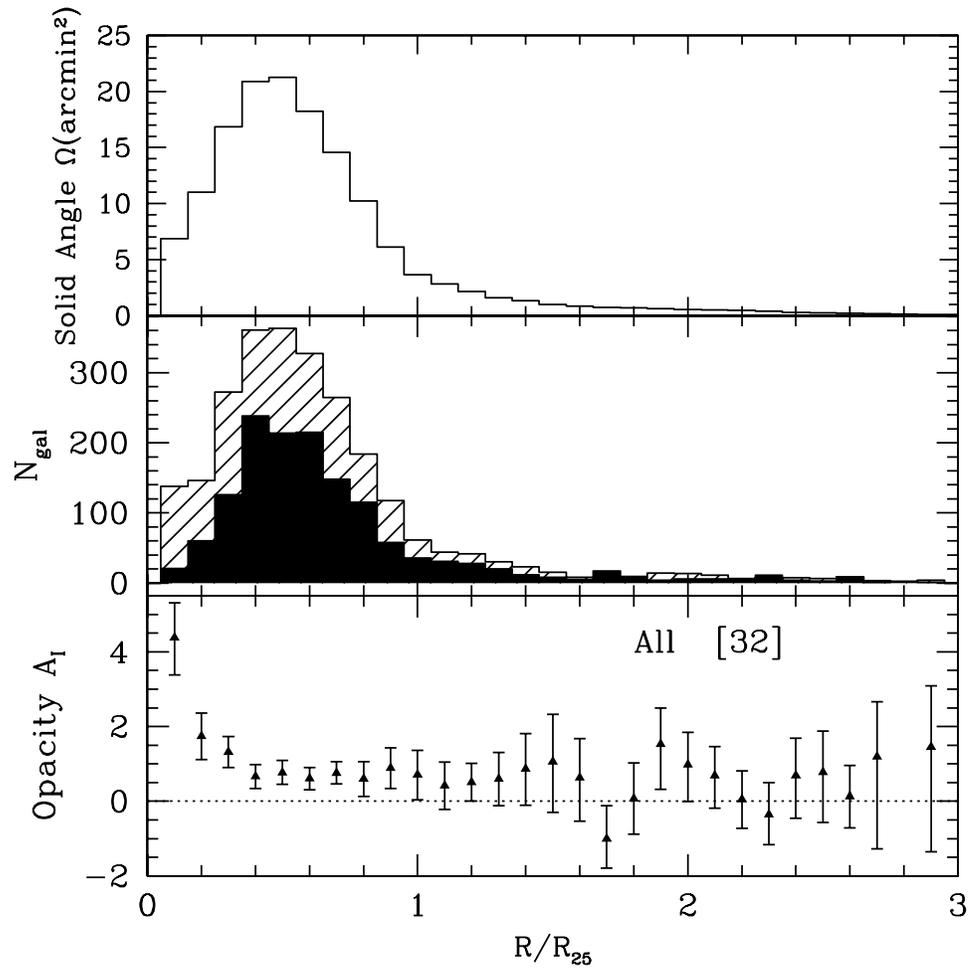


Figure 1. Radial opacity profile (bottom panel) from (Holwerda et al. 2005b), the numbers of real and artificial galaxies on which the opacity measurement is based (middle), and the combined solid angle in each radial bin (top). Galaxy counts at higher radii (for instance, the GHOSTS data, de Jong et al, this volume), and large mosaics on single disks will allow us to better characterize the point where disks become completely transparent.

1998; Holwerda et al. 2005a). We have obtained calibrated galaxy counts for a sample of 32 deep *HST/WFPC2* fields. The main results from the disk opacity study are: (1) most of the disks are semi-transparent (Holwerda et al. 2005b, Figure 1), (2) arms are more opaque (Holwerda et al. 2005b), (3) as are brighter sections of the disk (Holwerda et al. 2005e). We did not find a relation between HI profiles and disk opacity but this can be better explored on a single disk (Holwerda et al. 2005c). The optimal distance of the foreground disk is  $\sim 10$  Mpc, the compromise between crowding effects and solid angle constraints (González et al. 2003; Holwerda et al. 2005d).

The sample from Holwerda et al. (2005b) has an overlap of 12 galaxies with *SINGS*; we compared the disk opacity from number of distant galaxies to the dust surface density obtained from an SED model (Draine and Li 2007). Expressed as optical depths, the relation between the *observed* optical depth ( $\tilde{\tau}$ ) and the optical depth inferred from the SED dust mass ( $\tau_m$ ) is solely a function of the typical cloud optical depth ( $\tau_c$ ):  $\tilde{\tau}/\tau_m = (1 - e^{-\tau_c})/\tau_c$  (Natta and Panagia 1984). Figure 2 shows the values for  $\tilde{\tau}$  and  $\tau_m$  and the fit of  $\tau_c=0.4$ . This implies that most of the disks are made up of small, optically thin, cold ISM structures with more than one cloud along the line-of-sight, especially in optically thick disks (Holwerda et al. 2007a). From their distribution in the E[I-L] color map, it becomes clear that the number of distant galaxies does not drop exclusively as a result of grand spiral opaque structures but that the unresolved dusty ISM disk is equally important (Holwerda et al. 2007c).

## 2. Occulting Galaxies

A galaxy partially occulted by a face-on spiral galaxy can be used to determine the opacity of the foreground spiral. The method has seen extensive use on nearby pairs, using ground-based imaging (Andredakis and van der Kruit 1992; Berlind et al. 1997; Domingue et al. 1999; White et al. 2000), spectroscopy (Domingue et al. 2000) and, more recently, *HST* imaging (Keel and White 2001a,b; Elmegreen et al. 2001). Results from these included radial plots of extinction all the way through the disk, showing gray extinction when taken over large sections, but with a near-galactic reddening law for scales smaller than 100 pc, when resolved with *HST*.

The Sloan Digital Sky survey is a powerful tool for finding rare objects such as the ideal occulting pair, a face-on spiral partially covering a more distant elliptical. From the SDSS spectra, we selected 86 galaxy pairs, with emission spectra at lower redshift on top of an elliptical spectrum (similar to Bolton et al. 2004). We have applied the occulting galaxy method on the SDSS images, obtaining an opacity measurement at a single radius for many of these pairs. Figure 3 shows the radial opacity plot for local spirals, and for two more distant redshift bins from the SDSS. Close to the center of the spirals there is not enough flux from the background elliptical, but the radial profiles at  $z = 0-0.1$  and  $z = 0.1-0.2$  are similar to the local one for a mix of arm and disk values.

*HST* imaging of these pairs would allow us to (a) measure the opacity closer to the spiral's centre and (b) distinguish between arm and disk regions, and trace the radial opacity profile fully.

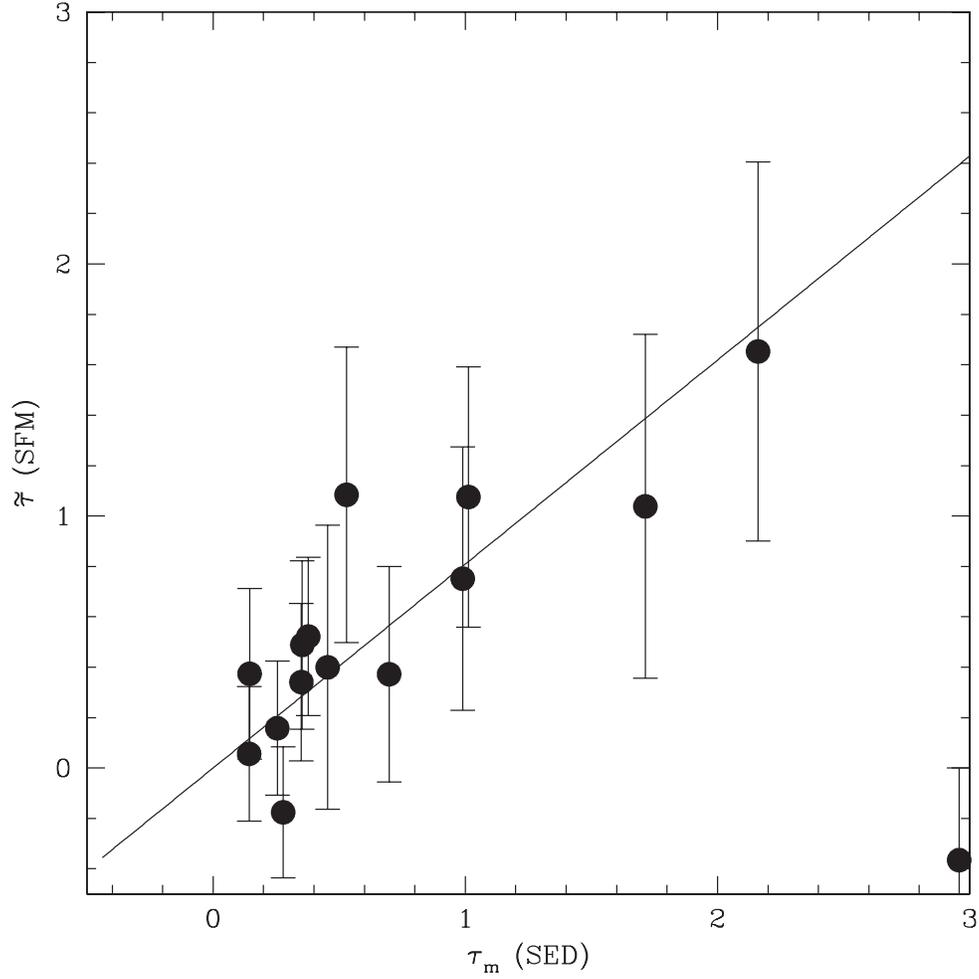


Figure 2. The relation between the optical depth from the SED model [ $\tau_m$ (SED)], and the observed optical depth from the number of distant galaxies [ $\tau$ (SFM)]. Model C from Natta and Panagia (1984) is fit through these. Cloud optical depth is 0.4, and more than a single cloud along the line-of-sight is needed, especially for optically thick disks. Figure from Holwerda et al. (2007a).

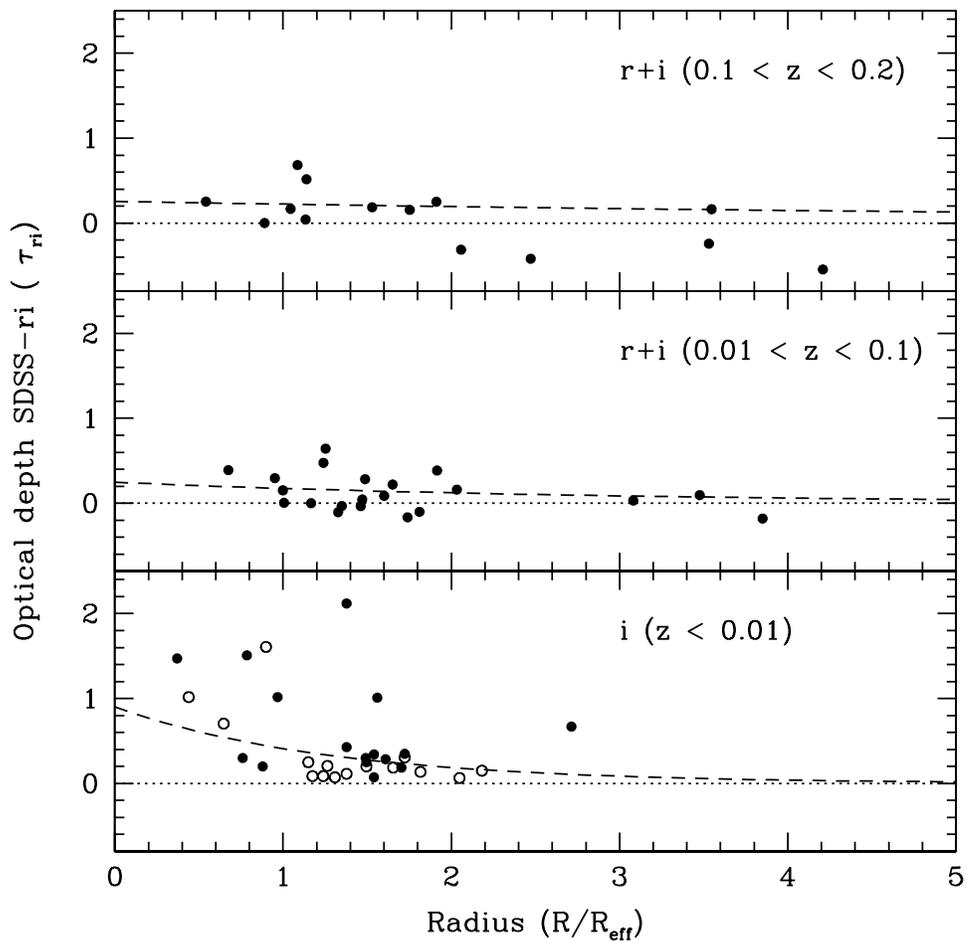


Figure 3. Radial opacity profile for the local (lower),  $z=0-0.1$  (middle) and  $z=0.1-0.2$  (top) spirals from occulting pairs. Open circles are disk sections for the local pairs. Figure from Holwerda et al. (2007b).

*HST* images of more distant pairs opens the opportunity to expand the redshift range of this technique. However, the method becomes less accurate with less-than-ideal pairs as the assumption of symmetry in both galaxies becomes less valid. To obtain an accurate radial extinction profile to redshift of 1, we would need several hundreds of bona-fide occulting pairs. The biggest obstacle to this work is a clear way of identifying these in current deep surveys with *HST* but a similar spectral identification in the DEEP2 survey has yielded 101 occulting pairs (See Figure 4).

In the nearby Universe, the GalaxyZoo project (Raddick et al. 2007) is identifying occulting pairs made up of various morphological types at a prodigious rate in the SDSS (the count was at 800 additional pairs in January 2008). These will help nail down the opacity profile in the near universe ( $z < 0.2$ ) as a reference for the *HST* imaging at higher redshifts.

### 3. Future Outlook

One can now confidently state that we know the dust content and the resulting extinction in local spiral disks within the optical radius. However, two issues remain: how far outside the optical disk can we detect the effect of dust and how much has the opacity of spiral disks changed since  $z \sim 1$ , when star formation was an order of magnitude higher? The radial extent can be explored with galaxy counts in large *HST* mosaics of local disks or with deep FIR *Spitzer* observations (See Hintz, *this volume*), and the evolution of disk opacity with large numbers of occulting pairs from both SDSS and *HST* deep surveys.

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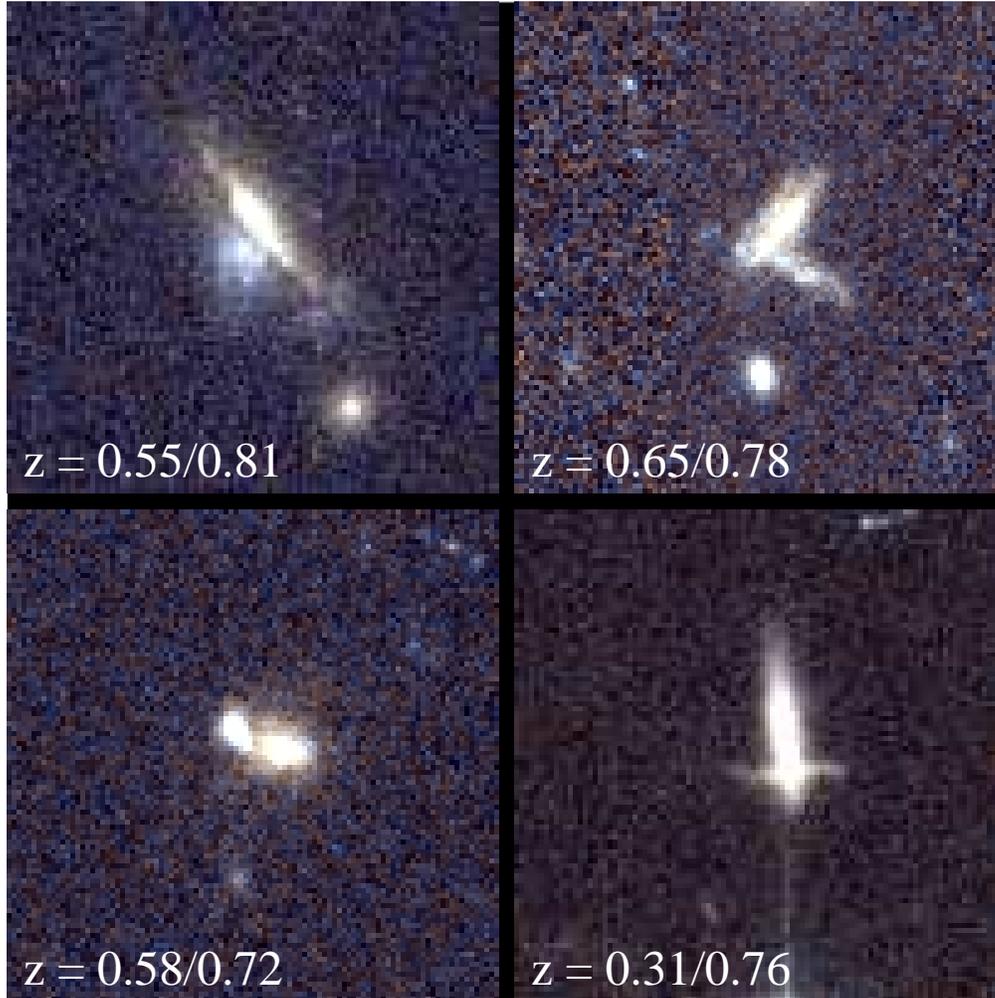


Figure 4. Examples of occulting pairs in the DEEP2 (Madgwick et al. 2003) survey, identified from their mixed-type spectra. The redshift of pair members is in the left-bottom corner of each postage stamp. These pairs are images with HST/ACS in the extended Groth strip and many more pairs are likely in the GEMS, GOODS and COSMOS fields. However, spectroscopic identification is the most reliable way to identify these.

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