Dust in galaxies

The effects of absorbing material in galaxies were recognized before the physical nature of galaxies became clear. A study by H.D. Curtis published in 1918 compared photographs of spirals in an obvious inclination sequence, showing that a band of obscuring material lies in the disk plane.

- **Screen model**
Take a foreground screen of optical depth τ. Then the observed surface brightness is $I = I^0\, e^{-\tau}$, where I^0 – true surface brightness ($i = 90^{\rm o}$).

The face-on extinction in the apparent mag. scale is $A = -2.5\,\lg\frac{I}{I^0} = 1.086\,\tau$.

- **Slab model**
Uniform density well-mixed slab of stars, gas and dust of physical depth H, volume emissivity ϵ_* (total luminosity of stars per unit of volume) and with a mean free path to its own stellar radiation of l.

We can calculate the face-on optical surface brightness by integrating the contributions from elements at diferent depths x as

$$I(i = 0^{\rm o}) = \int_0^H \epsilon_* e^{-x/l} dx = \epsilon_* l \left[1 - e^{-\tau}\right],$$

where $\tau = H/l$ is the total optical depth of the slab to optical radiation.
In the optically thin limit ($\tau << 1$) we therefore have
$I(i = 0^{\rm o}) = \epsilon_* H$,
while in the optically thick limit ($\tau >> 1$)
$I(i = 0^{\rm o}) = \epsilon_* l$.

When inclined ($i \neq 0^{\rm o}$)

$$\begin{array}{ccc} H & \rightarrow & H \sec i \\ \tau & \rightarrow & \tau \sec i \end{array}$$

Thus

$$I(i) = \epsilon_* l \left[1 - e^{-\tau \sec i}\right].$$

For the optically thick case, $I(i) = I(i = 0^{\rm o}) = \epsilon_* l$, which is independent of i.

But, for the optically thin slab, $I(i) = \epsilon_* H \sec i = I(i = 0^{\rm o}) \sec i$, which increases as $\sec i$.
Last formula can be rewritten as $\mu_0^{obs} = \mu_0^{face-on} - 2.5\,\lg\sec i$.
$\sec i$=1/$\cos i$, thin disk: $\cos i$=b/a, therefore, we obtain standard correction to "face-on" orientation – $\mu_0^{obs} = \mu_0^{face-on} - 2.5\,\lg\frac{a}{b}$.

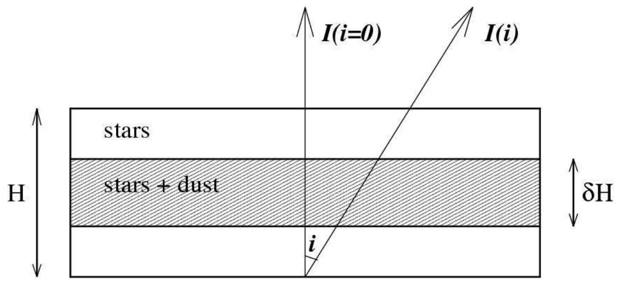
Face-on extinction in the mag. scale:

$$A = -2.5\,\lg\frac{\epsilon_* l\,[1 - e^{-\tau}]}{\epsilon_* H} = -2.5\,\lg\frac{1 - e^{-\tau}}{\tau}.$$

Compared with a screen, a given slab extinction corresponds to a significantly greater optical depth, because not all of the dust in a slab obscures all of the stars.

For instance, $\tau = 5 \Longrightarrow A = 5.^m4$ (screen),
$A = 1.^m75$ (slab).

- Sandwich model



Total optical depth $\tau = \delta\, H/l$, $\delta = 1 \rightarrow$ slab model.

As a preliminary, consider an optically thick ($\tau >> 1$) sandwich seen from the pole. The lowest layer will be totally hidden; the upper crust will be quite unobscured and we will also see a distance l into the dusty layer. So, the surface brightness is $I(i = 0^{\rm o}) \approx \epsilon_* H(1 - \delta)/2 + \epsilon_* l$.
In the absence of extinction ($\tau = 0$) $I(i = 0^{\rm o}) = \epsilon_* H$.
Therefore,

$$A = -2.5\,\lg[(1 - \delta)/2 \,+\, \delta/\tau]$$

($\tau >> 1$).

The observed surface brightness of an inclined sandwich:

$$I(i) = \epsilon_* H \sec i \left[\frac{1-\delta}{2}(1 + e^{-\tau \sec i}) + \frac{\delta}{\tau \sec i}(1 - e^{-\tau \sec i})\right].$$

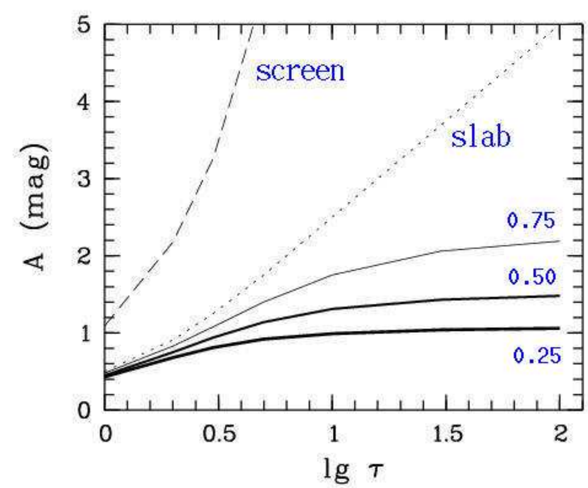
Thus, for an opaque sandwich ($\tau >> 1$ or $e^{-\tau} << 1$) with $\delta = 0.5$:

$$I(i) \approx \epsilon_* H \sec i/4 \;=\; I(i = 0^{\rm o}) \sec i/4.$$

The surface brightness behaves just as it would in an optically thin slab as deep as the unobscured upper crust ($H/4$).

The face-on extinction:

$$A = -2.5\,\lg\left[\frac{1-\delta}{2}(1 + e^{-\tau}) + \frac{\delta}{\tau}(1 - e^{-\tau})\right].$$



Face-on extinction ($i = 0^{\rm o}$) vs. optical depth.

- Triple exponential model

More realistic model:
radial distributions of stars and dust are exponential with the same scale length value h, vertical exponential scale height of stars – z_*, dust – $z_d = \delta\, z_*$.

The problem is not simple (we must solve the radiative transfer equation). There is a good analytical approximation to the observed surface brightness, valid for thin ($z_* << h$) and not exactly edge-on ($i \leq 80^{\rm o}$) disk (Disney et al. 1989):

$$I(r) = 2I(0,0)z_* \frac{\theta}{\cos i} e^{-r/h},$$

where

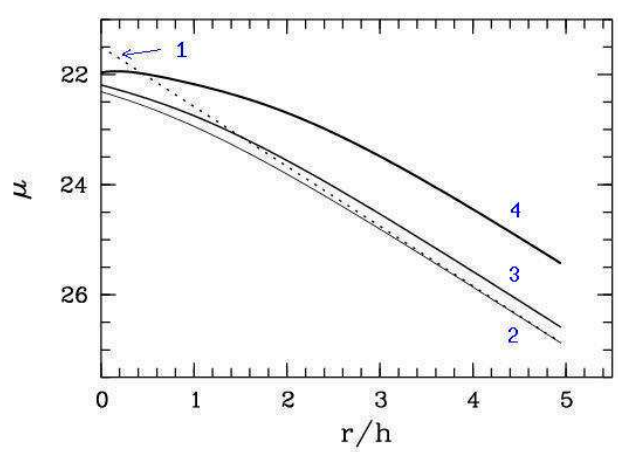
$$\theta = e^{-\tau}\left[1 + \frac{\tau^2}{(\delta+1)(\delta+2)} + \frac{\tau^4}{(\delta+1)(\delta+2)(\delta+3)(\delta+4)}\dots\right],$$

$$\delta = z_d/z_* = \left(\frac{\sin i}{h} + \frac{\cos i}{z_*}\right) / \left(\frac{\sin i}{h} + \frac{\cos i}{z_d}\right)$$

and

$$\tau = \frac{\tau_0}{\cos i} e^{-r/h}$$

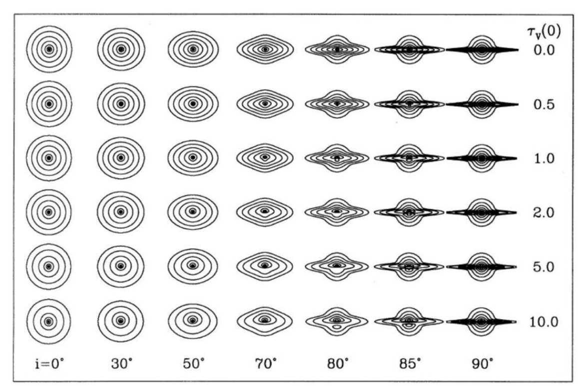
(τ_0 – central optical depth of the disk at $i = 0^{\rm o}$).

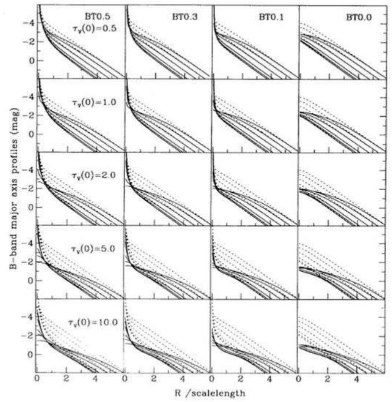


Sumulations results according to analytical formula for triple exponential model: (1) transparent, dust-free exponential disk; (2) disk with $\tau_0 = 1$ and $i = 0^{\rm o}$; (3) $\tau_0 = 1$ and $i = 40^{\rm o}$; (4) $\tau_0 = 1$ and $i = 75^{\rm o}$.

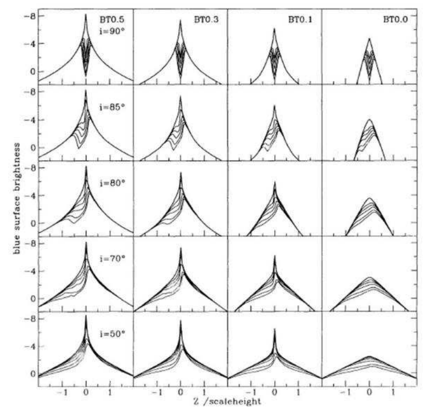
- Numerical modelling

Byun et al. (1994):
the radiative transfer including both scattering and absorption has been computed for a range of model spiral galaxies with immersed dust layers.





Major axis profiles in the *B* band (*solid lines*). Each panel shows the surface brightness profiles along the major axis for a given optical depth and inclinations 85°, 80°, 70°, 50°, 30°, and 0° from top to bottom. The dashed lines are for dust-free galaxies, showing the geometric projection effect for $i = 85°, 80°, 70°, 50°, 30°$, and 0° from top to bottom.



Minor axis profiles in *B* for the inclinations shown and optical depths $\tau_V(0) = 0$ (*top thick solid lines*) and $\tau_V(0) = 0.5$, 1, 2, 5, and 10 from top to bottom. The negative *z*-axis corresponds to the half of the galaxy closer to the observer.

Byun et al. (1994)

Some conclusions:

- The minor-axis profiles in spiral galaxies with inclinations $0^{\circ} < i < 90^{\circ}$ show a characteristic asymmetry due to dust.
- The apparent galactic center of inclined galaxies is displaced from its true position when there is dust present.
- A color gradient is predicted in dusty spiral galaxies.
- The inferred scale lenght of a dusty spiral galaxy is different in different bands.
- The internal extinction of a galaxy in one band cannot be converted to that in another band by simply using an extinction law.
- An optical depth of order 1 through the center of a face-on spiral galaxy implies that the galaxy is effectively transparent. However, if the same galaxy is seen edge-on it will exhibit a prominent dust lane.

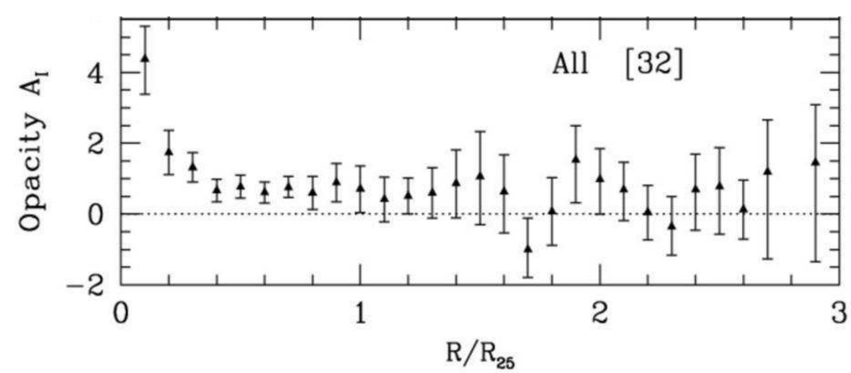
Distribution of dust and value of τ

Two observational methods have produced relible measurements of disk opacity:
occulting galaxy pairs and the calibrated number of more distant galaxies.

- *Distant galaxy counts*

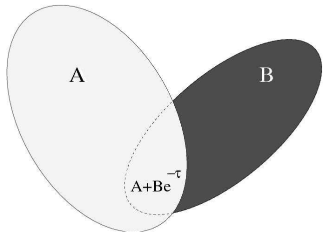
The number of distant galaxies seen through the face-on foreground spiral is a direct indication of its opacity, after proper calibration using artificial galaxy counts.
Holwerda et al. (2005): galaxy counts for a sample of 32 deep HST/WFPC2 fields. The main results are:

(1) most of the disks are semi-transparent;
(2) spiral arms are more opaque;
(3) as are brighter sections of the disk.



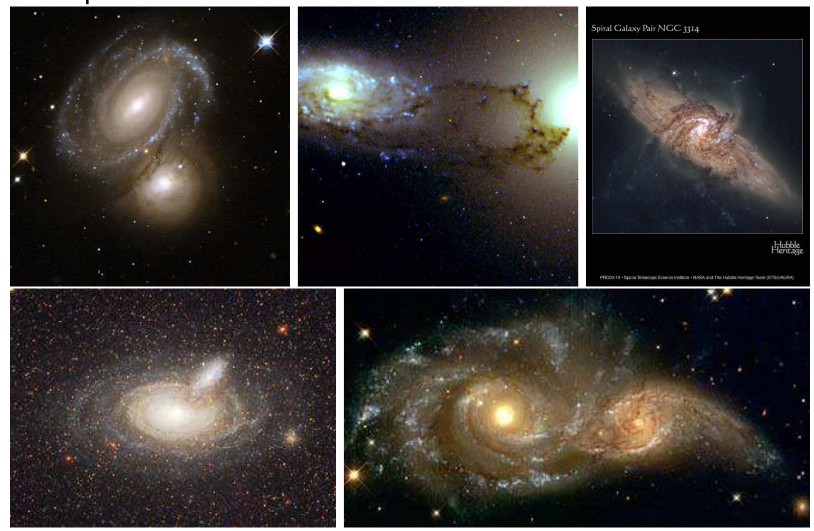
Radial opacity profile from Holwerda et al. (2005)

- *Occulting galaxies*



Ideal case: relatively face-on spiral (A) backlit by a partly occulted, preferably early type, galaxy (B).
Basic assumption: light from both the occulted galaxy and the foreground galaxy is sufficiently symmetric to characterize the contributions in the overlapping region from the unprojected parts of the galaxies.

Examples:



Main conclusions from various approaches:

- Disks are more opaque in the blue and are practically transparent in the near-infrared.
- Disks are practically transparent in the outer parts but show significant absorption in the inner regions ($\tau_0(V) \sim 1-3$).
- The extinction correlates with galaxy luminosity ($\tau \propto L^{0.5}$).
- Spiral arms are more opaque than the disk.
- $\langle h_{dust}/h_{stars}\rangle \approx 1-1.5$, $\langle z_{stars}/z_{dust}\rangle \approx 2$ (V passband).

Standard corrections

- Total luminosity

$$A_i = C_L(T)\,\lg\,(a/b)_{25}, \qquad \text{(RC3 catalog)}$$

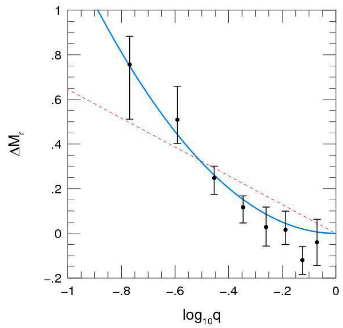
where C_L depends on the wavelength and on the morphological type. In the B filter
$C_L = 1.5 - 0.03\cdot(T-5)^2 \quad (T \geq 0)$,
$C_L = 0 \quad (T < 0)$.
Example: Sc galaxy ($T = 5$) with $b/a = 0.10$ at edge-on orientation looks fainter by $1.^m5$ than face-on.

Tully et al. (1998) found dimming that was dependent on mass (luminosity) as well as on wavelength:
$C_L(B) = 1.57 + 2.75(\lg W^i - 2.5)$, where $W^i \approx 2\mathrm{V}_{max}$.

Therefore, for Milky Way type galaxy with V_{max}=220 km/s $C_L = 2.^m0$.

Unterborn & Ryden (2008): analysis of 78 230 galaxies in the SDSS survey (r-band, $\lambda_{eff} = 6250$Å).

The dimming is well described by the relation $\Delta M_r \propto (\lg b/a)^2$, rather than standard $\Delta M_r \propto \lg b/a$.



The dashed red curve shows $\Delta M_r = -0.64 \lg b/a$, and the solid blue curve shows $\Delta M_r = 1.27 (\lg b/a)^2$

• Disk central surface brightness

Standard correction:

$$\mu_0^{face-on} = \mu_0^{obs} + 2.5\, C_\mu \lg \frac{a}{b},$$

where $C_\mu = 1$ for transparent disk,
$C_\mu = 0$ for optically thick, opaque disk.

Real galaxies – $C_\mu \sim 0.5$.

• Color indices

$$\Delta(B - V) = C_c(T) \lg (a/b)_{25}, \qquad \text{(RC3 catalog)}$$

where $C_c = 0.35 - 0.022 \cdot (T - 3)^2 \quad (-1 \leq T \leq 7)$,
$C_c = 0 \quad (T \leq -1,\ T \geq 7)$.

Therefore, Sc galaxy ($T = 5$) with $b/a = 0.10$ looks redder by $\Delta(B - V) = +0.26$ at $i = 90^{\rm o}$ than at $i = 0^{\rm o}$.

• Inclination dependence of the isophotal radius

Standard corrections:

$$h_i/h_0 = 1 + \eta \lg (a/b),$$

h_i and h_0 are exponential scale length values at arbitrary and zero inclinations and $\eta \approx 0.3 - 0.4$.

$$R_i^{23.5}/R_0^{23.5} = (a/b)^{C_D},$$

$R^{23.5}$ is the isophotal radius at $\mu(I) = 23.5$ and $C_D \approx 0.2$.

Example: $R_{90}^{23.5}/R_0^{23.5} \approx 1.6$ for $b/a = 0.10$.