# STRUCTURE OF GALAXIES

## 8. Absorption; chemical evolution

Piet van der Kruit

Kapteyn Astronomical Institute

University of Groningen

the Netherlands

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Absorption
Chemical evolution

Holmberg's analysis
Analysis of Disney et al.
Edge-on galaxies
Background galaxies

# Absorption

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# Holmberg's analysis

The earliest study is by Holmberg[1].

He defined an apparent face-on surface brightness from the apparent magnitude $m$ and and the angular major-axis diameter $a$

$$\mu'_{\mathrm{obs}} = m + 5 \log a$$

He then plotted this against the axis ratio $b/a$ on the sky.

The inclination $i$ is related to the axis ratio as

$$\sec i = a/b$$

for a not too edge-on disk ($a/b < 3$).

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[1]E. Holmberg. Medd. Lund Obs. Ser. 2, No. 136 (1958)

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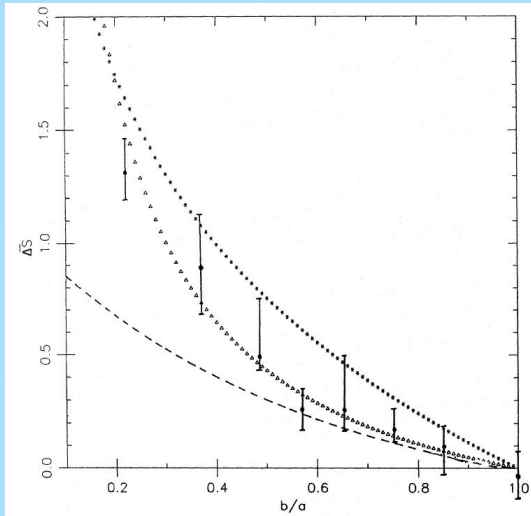
Holmberg's fit to the data (triangles) then is

$$\mu'_{\mathrm{obs}}(i) = \mu'(0) + A_{\mathrm{B}}\{\sec i - 1\}$$

$A_{\mathrm{B}} = 0.40$ mag for Sa-Sb
$A_{\mathrm{B}} = 0.28$ mag for Sc

So his conclusion was that disk of galaxies are not optically thick.

However, it should be realised that Holmberg's fit is not physical, since it is actually that of a dust sheet in front of a stellar disk.

Later with the IRAS satellite is was found that often for galaxies $L_{\mathrm{FIR}}/L_{\mathrm{opt}} \sim 1$ or more.

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Realise that for a thin, opaque dust layer in the central plane of stellar disk we expect:

- $A_{\mathrm{B}} = 0.75$ mag.
- No change in color index
- $L_{\mathrm{FIR}}/L_{\mathrm{opt}} \sim 1$

In the Galaxy we are *not* in an optically thick part of the disk.

Extinctions towards the poles are estimated between 0 and 0.2 mag in B.

But there may be denser parts and towards the center absorption may in general increase in galaxies.

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## Analysis of Disney et al.

Disney *et al.*[2] collected information from various sources, parametrizing it as

$$\mu_{\rm obs}(i) = \mu_{\circ} - 2.5 n_{\rm eff} \log(a/b)$$

In a completely optically thin disk one expects $n_{\rm eff} = 1$ and in an optically thick disk $n_{\rm eff} \leq 1$.

Then for samples in the Second Reference Catologue (RC2) and the Revised Shapley-Ames Catalogue (RSA) the following values are found for $n_{\rm eff}$:
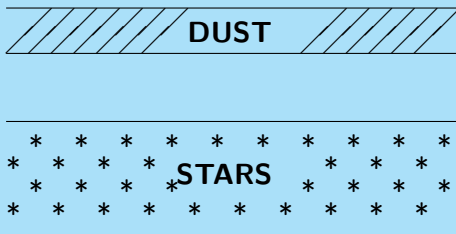
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[2]M. Disney, J. Davies & S. Phillipps, Mon.Not.R.A.S. 239, 939 (1989)

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| Type | Holmberg | RC2 | RSA |
|---|---|---|---|
| Sa-Sb | 0.46 | 0.72 | 0.46 |
| Sbc | 0.46 | 0.68 | 0.65 |
| Sc | 0.65 | 0.68 | 0.65 |
| Sd | - | 0.68 | 0.65 |
| Sdm-Im | - | 0.96 | 0.82 |

So there is certainly evidence for some absorption.

Now look at some simple models of Disney *et al.*

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## ♠ SCREEN MODEL



The dust layer has optical thickness $\tau$, the stellar disk emissivity $E^*$ and thickness $T$.

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The observed surface brightness the becomes

$$L(i) = E^* T \sec i \exp\{-\tau \sec i\}$$

Note that Holmberg's $\mu'$ is $L'(i) = L(i) \cos i$, so

$$\mu'(i) = \mu'_\circ + A^\circ_B \sec i = \mu'(0) + A^\circ_B(\sec i - 1)$$

The total face-on absorption becomes

$$A^\circ_B = 1.086\tau$$

For $\tau \ll 1$

$$L(i) = E^* T \sec i$$

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The observed surface brightness is $L(\tau, i)$ and the bolometric surface brightness is $L(0, 0) \sec i$.

Consider a circular area $\pi a^2$, then total luminosity is

$$L_{\rm bol} = \pi a^2 L(0, 0) = \pi a^2 E^* T$$

The observed face-on luminosity is

$$L_{\rm opt} = \pi a^2 L(\tau, 0)$$

If the dust re-radiates isotropically

$$L_{\rm FIR} = L_{\rm bol} - L_{\rm opt} = \pi a^2 \{L(0, 0) - L(\tau, 0)\}$$

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The FIR surface brightness at inclination $i$ then is

$$L_{\mathrm{FIR}}(i) = \sec i \{ L(0,0) - L(\tau, 0) \}$$

and we can calculate (drop the $\tau$'s)

$$\frac{L_{\mathrm{FIR}}}{L(i)} = \sec i \frac{E^* T - L(0)}{L(i)}$$

So we get for the Screen Model

$$\frac{L_{\mathrm{FIR}}}{L(i)} = \exp \{ \tau \sec i \} - 1$$

For the optically thin case $\tau \ll 1$ this reduces to

$$\frac{L_{\mathrm{FIR}}}{L(i)} = \tau \sec i$$

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## ♠ SLAB MODEL

Now make the model more realistic.



The results then become:

$$L(i) = \frac{E^* T}{\tau} \left[ 1 - \exp\left\{ -\tau \sec i \right\} \right]$$

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$$A_{\mathrm{B}}^{\circ} = -2.5 \log \left\{ \frac{1 - \exp(-\tau)}{\tau} \right\}$$

$$\frac{L_{\mathrm{FIR}}}{L(i)} = \sec i \frac{\tau - 1 + \exp\{-\tau\}}{1 - \exp\{-\tau \sec i\}}$$

For the optically thick case $\tau \gg 1$

$$L(i) = \frac{E^* T}{\tau} = \text{constant}$$

$$A_{\mathrm{B}} = 2.5 \log \tau$$

$$\frac{L_{\mathrm{FIR}}}{L(i)} = (\tau - 1) \sec i$$

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and for the optically thin case $\tau \ll 1$

$$L(i) = E^* T \sec i$$

So $L'$ is independent of $i$.

$$A_{\mathrm{B}} = -2.5 \log \left(1 - \frac{\tau}{2}\right)$$

$$\frac{L_{\mathrm{FIR}}}{L(i)} = \frac{\tau}{2}$$

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## ♠ SANDWICH MODEL

In real galaxies the dust layer is thinner than the stellar disk.



Let the thickness of dust layer be $pT$. Then

$$L(i) = E^* T \sec i \left[ \frac{1-p}{2} \{1 + \exp(-\tau \sec i)\} + \frac{p}{\tau \sec i} \{1 - \exp(-\tau \sec i)\} \right]$$

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The optically thick case $\tau \gg 1$ now becomes

$$L(i) = E^* T \sec i \, \frac{1-p}{2}$$

$$A_{\mathrm{B}} = -2.5 \log \left\{ \frac{1-p}{2} \right\}$$

$$\frac{l_{\mathrm{FIR}}}{L(i)} = \sec i \frac{(1+p)\tau - 2p}{(1-p)\tau + 2p}$$

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If $p \ll 1$

$$L(i) = \frac{E^* T}{2} \sec i$$

$$A_{\mathrm{B}} = 0.753$$

$$\frac{L_{\mathrm{FIR}}}{L(i)} = \sec i$$

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The optically thin case $\tau \ll 1$ gives

$$L(i) = E^* T \sec i \left\{ 1 - \frac{1-p}{2} \tau \sec i \right\}$$

$$A_{\mathrm{B}} = -2.5 \log \left\{ 1 - \frac{1-p}{2} \tau \right\}$$

$$\frac{L_{\mathrm{FIR}}}{L(i)} = \frac{\tau}{2}$$

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If $p \ll 1$

$$L(i) = E^* T \sec i \left(1 - \frac{\tau}{2} \sec i\right)$$

$$A_{\mathrm{B}} = -2.5 \log \left(1 - \frac{\tau}{2}\right)$$

$$\frac{L_{\mathrm{FIR}}}{L(i)} = \frac{\tau}{2}$$

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• triangles: $\tau < 1$ Screen Model
• stars: $\tau \gg 1$ Slab Model
• dashes: $\tau \gg 1$ Sandwich Model ($p = 0.5$).

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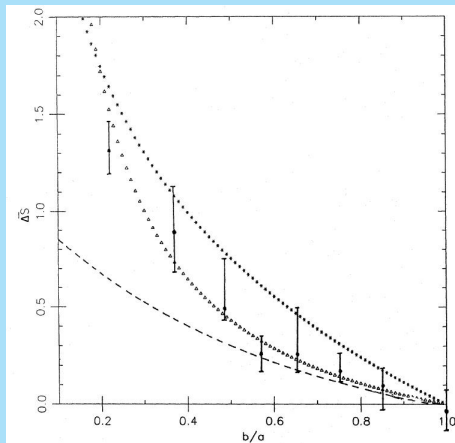
The optically thin Slab and Sandwich Models predict no dependence of Holmberg surface brightness on inclination.

So observations are consistent with optically thick models, but the results are very geometry dependent and therefore not yet conclusive.

The near-IR data are also not entirely conclusive. $L_{\mathrm{FIR}}$ can be very large compared to $L_{\mathrm{opt}}$ if star-formation occurs extensively in very thick, obscured, but localized area's (GMC's)

Disney *et al.* also calculate triplex models as above, which give similar results as these simple models.

We can still extend the analysis by looking at the colors.

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In all models we had:

$$L(i) = E^* TF(p, \tau, i) \sec i$$

Take

$$\tau_V = 0.75 \tau_B$$

$$\frac{L_B(i)}{L_V(i)} = \frac{E^*(B)}{E^*(V)} \frac{F(p, \tau_B, i)}{F(p, \tau_V, i)}$$

The color change between inclination $0°$ and $70°$ then is:

$$\Delta(B - V) = -2.5 \log \left\{ \frac{F(p, \tau_B, 70) F(p, \tau_V, 0)}{F(p, \tau_V, 70) F(p, \tau_B, 0)} \right\}$$

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For the Sandwich Model we have:
- Optically thin ($\tau \ll 1$):

$$F(p, \tau, i) = 0.5 \Rightarrow \Delta(B - V) = 0$$

- Optically thick ($\tau \gg 1$):

$$F(p, \tau, i) = \frac{1 - p}{2} \Rightarrow \Delta(B - V) = 0$$

Here are some values for $\Delta(B - V)$ as a function of optical thickness.

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| $\tau$ | Screen | p = 1 | p = 0.5 | p = 0.1 |
|--------|--------|-------|---------|---------|
| 0.1    | 0.05   | 0.02  | 0.02    | 0.02    |
| 0.5    | 0.26   | 0.09  | 0.06    | 0.04    |
| 1.0    | 0.52   | 0.13  | 0.04    | -0.01   |
| 2.0    | 1.04   | 0.11  | -0.04   | -0.07   |
| 5.0    | 2.61   | 0.02  | -0.04   | -0.01   |
| 10.    | 5.22   | 0.02  | 0.02    | 0.02    |

• For small $\tau$ B is always more affected than V, so redder with inclination.

• For large $\tau$ at high inclination we see only up to the dust, so we have unreddened colors.
However at face-on there is still reddening and disks become bluer with inclination.

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## Edge-on galaxies

Kylafis & Bahcall[3] model the surface brightness distribution of NGC 891.

They assume for the space density of stars

$$L(R, z) = L_{\rm o} \exp\left(-\frac{R}{h_{\rm s}}\right) \, {\rm sech}^2\left(\frac{z}{z_{\rm s}}\right)$$

and for the dust (absorption coefficient)

$$\kappa(R, z) = \kappa_{\rm o} \exp\left(-\frac{R}{h_{\rm d}}\right) \, {\rm sech}^2\left(-\frac{z}{z_{\rm d}}\right)$$

[3]N. Kylafis & J.N. Bahcall, Ap.J. 317, 637 (1987)

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This produces very good fits of z-profiles with:

$$
\begin{aligned}
z_{\mathrm{s}} &\sim 0.93 \ \mathrm{kpc} \\
z_{\mathrm{d}} &\sim 0.22 \ \mathrm{kpc} \\
h_{\mathrm{s}} &\sim 4.9 \ \mathrm{kpc} \\
h_{\mathrm{d}} &\sim (0.8 - 1.5)h_{\mathrm{s}} \\
\tau_{\mathrm{o}} = 2\kappa_{\mathrm{o}}h_{\mathrm{d}} &\sim 10.3
\end{aligned}
$$

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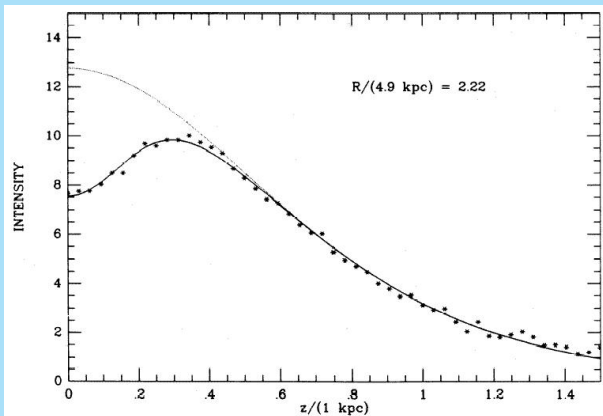
Translated to face-on this is:

$$\tau(R) = 2\kappa_\circ z_{\rm d} \exp\left(-\frac{R}{h_{\rm d}}\right) = 0.46 \exp\left(-\frac{R}{h_{\rm d}}\right)$$

An optical depth $\tau$ of 0.46 corresponds to an extinction of 0.50 mag.

For a central thin dust-layer this means, that we miss 58% of the light from the backside and the total disk surface brightness is decreased by 18%.

However, the $\mathrm{sech}^2$ may not be a good approximation at low $z$ due to young stars, in which case there is more extinction than implied here.

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Wainscoat *et al.*[4] make a similar model of IC 2531 on the basis of UBVRIJHK photometry.

They use exponentials in the $z$-direction: Old disk:

$$L_{\mathrm{old}}(R, z) = L_{\mathrm{old}}(0, 0) \exp \left( -\frac{R}{h} - \frac{|z|}{h_{\mathrm{z}}} \right)$$

Young disk:

$$L_{\mathrm{young}}(R, z) = L_{0,\mathrm{y}}(0, 0) \exp \left( -\frac{R}{h} - \frac{|z|}{h_{\mathrm{z,y}}} \right)$$

Dust absorption in path $\delta d$ along line-of-sight $d$:

$$\delta A_\lambda(R, z) = A_{\lambda,0} \exp \left( -\frac{R}{h_{\mathrm{d}}} - \frac{|z|}{h_{\mathrm{z,d}}} \right) \delta d$$

[4]R.J. Wainscoat, K.C. Freeman & A.R. Hyland, Ap.J. 337, 190 (1989)

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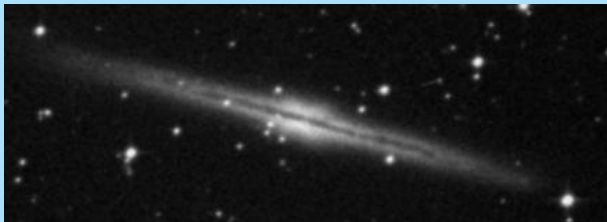


Adopted and resulting parameters:

| color | old disk | young disk | $\lambda$ | $A_\lambda/A_{\mathrm{V}}$ |
|-------|----------|------------|-----------|------------|
| U-V | 1.09 | -0.77 | U | 1.531 |
| B-V | 0.78 | -0.04 | B | 1.324 |
| V-R | 0.50 | -0.01 | R | 0.816 |
| V-I | 1.14 | 0.00 | I | 0.597 |
| V-J | 1.80 | 0.01 | J | 0.282 |
| V-H | 2.51 | 0.02 | H | 0.175 |
| V-K | 2.76 | 0.03 | K | 0.112 |

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$$h \quad \sim \quad 6.4 \text{ kpc}$$

$$h_{\text{z}} \quad \sim \quad 0.53 \text{ kpc}$$

$$h_{\text{z,d}} \quad = \quad h_{\text{z}}/4$$

$$h_{\text{z,y}} \quad = \quad h_{\text{z}}/8$$

$$A_{\text{V}}(0,0) \quad = \quad 1.6 \text{ mag kpc}^{-1}$$

$$L_{\text{young}}(0,0) \quad = \quad L_{\text{old}}(0,0) \text{ in V} - \text{band}$$

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Here are z-profiles in U, B, V, R, and I (top to bottom) in the
top-panel and in V, J, H and K in the bottom-panel.

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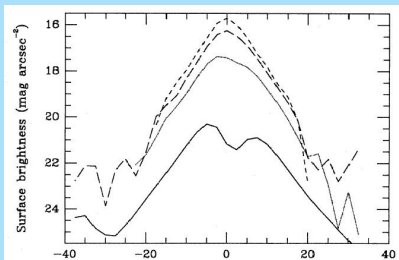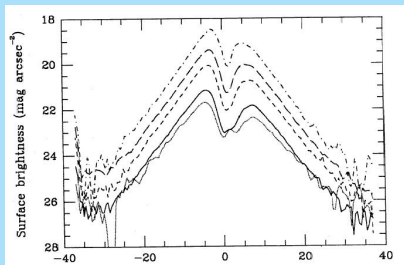
The models then give these profiles (U at the bottom, K at the top).
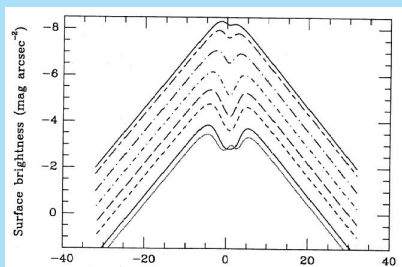


Also the color profiles can be calculated and compared to observations.

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We see first the observed profiles: from bottom to top (U - B), (B - V), (V - R) and (V - I) in the top-panel and bottom to top (J - K) and (J - I) in the bottom panel.

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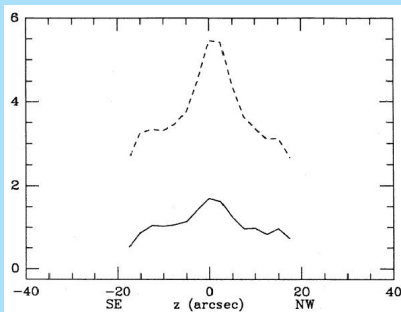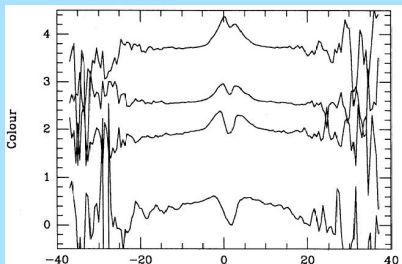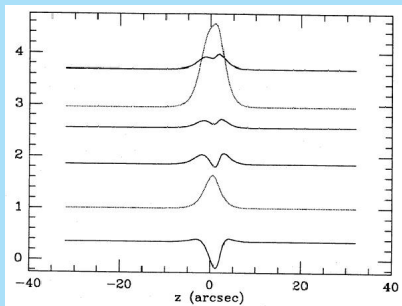


Here the color profiles from the model. Solid lines from bottom to top: (U - B), (B - V), V - R) and (V - I); dotted lines from bottom to top: (J - K) and (H - K).

Thus $A_{\mathrm{B}}(0,0) = 1.9$ mag kpc$^{-1}$ or $\kappa_\circ = 1.75$ kpc$^{-1}$.

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So we get face-on in the B-band:

$$\tau(R) = \kappa_\circ h_{z,d} \exp\left(\frac{R}{h}\right) = 2.80 \exp\left(-\frac{R}{h}\right)$$

A $\tau$ of 2.80 corresponds to an extinction of 3.0 mag. For a very

thin dust-layer the total light from the disk is decreased by 47%.

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• Valentijn[5] claimed that in complete samples the observed mean surface brightness correlates little with axis ratio (see next frame).

One expects more inclined galaxies to be systematically brighter in surface brightness.

So maybe disks are optically thick.

• Jura[6] proposed that Freeman's law results from absorption. He also noted the similar surface brightness in the (obscured!) Milky Way.

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[5] E.A. Valentijn, Mon.Not.R.A.S. 266, 614 (1994); also R. Burstein, 1980, unpublished
[6] M. Jura, Ap.J. 238, 499 (1980)

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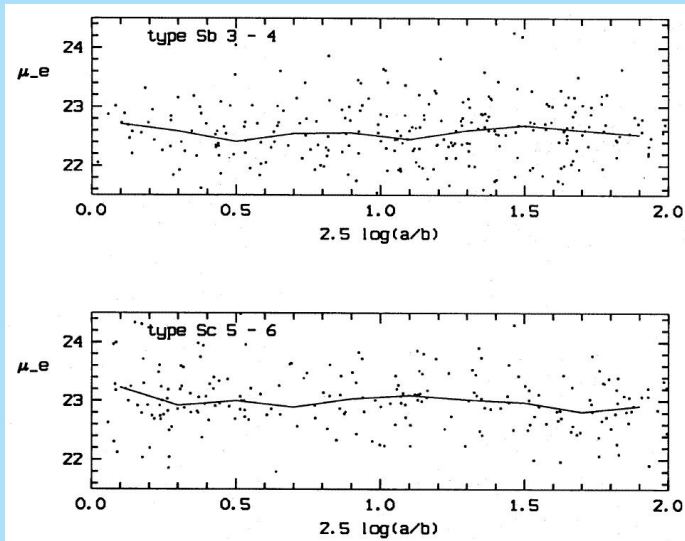
# Background galaxies

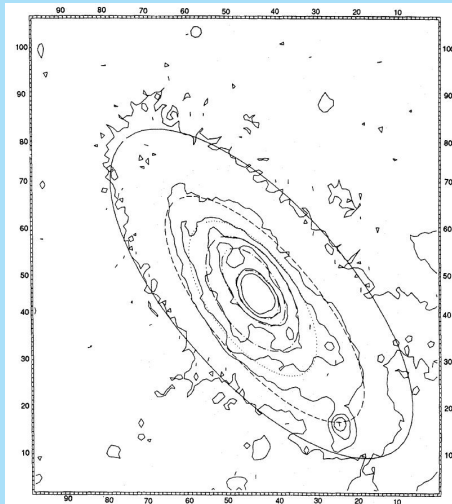A very effective test in principle is to look for galaxies seen through disks as in the pair NGC450/UGC807[7].



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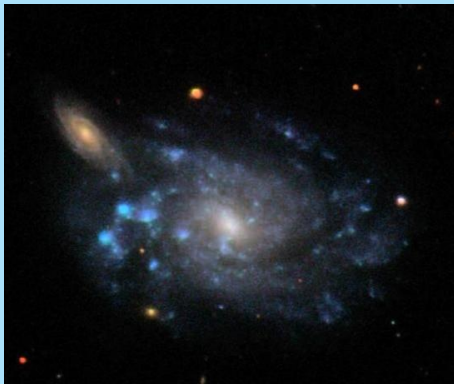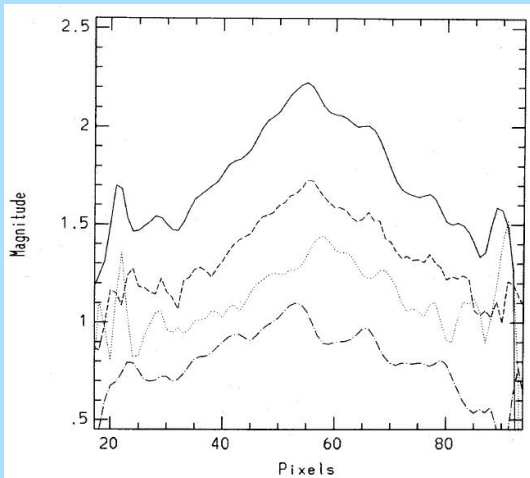
[7]Y. Andredakis & P.C. van der Kruit, A.&A. 265, 396 (1992)

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In the photometry we can deduce the surface brightness distribution of NGC 450 in the area of overlap.

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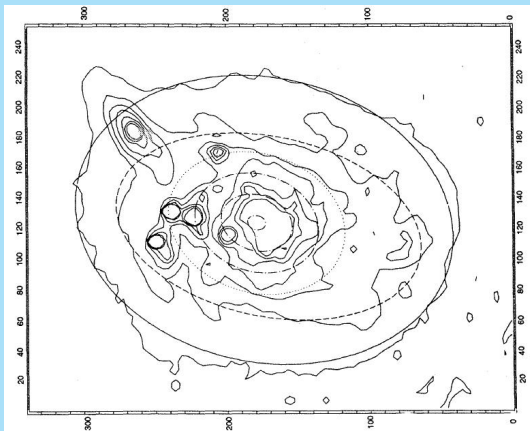
Subtraction then gives the "uneffected" image of UGC807.

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This shows no color changes, so there is no significant gradient in absorption.

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Both galaxies conform to the Tully-Fisher relation.

The maximum absorption allowed is 0.3 magnitudes in the V-band.

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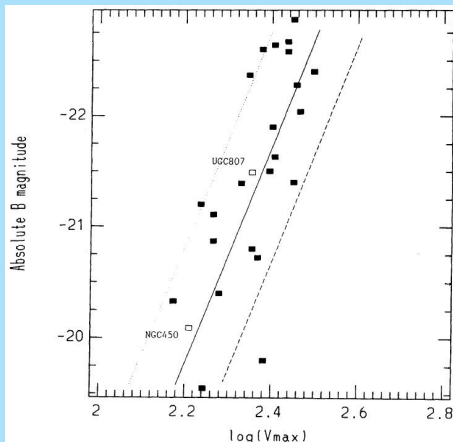
More sophisticated is to study images of galaxies with the Hubble
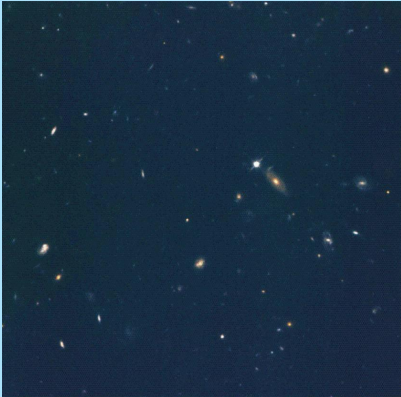Space Telescope and identify background galaxies.

For this one takes images from the HST archive, essentially from
the key-project to derive the distance scale through Cepheids and
calibration of the TF-relation[8].

Then the test can be done by adding the Hubble Deep Field
(HDF) with the appropriate noise and background level and see
what fraction of these galaxies are recovered.

With this synthetic field method[9] evidence for some absorption has
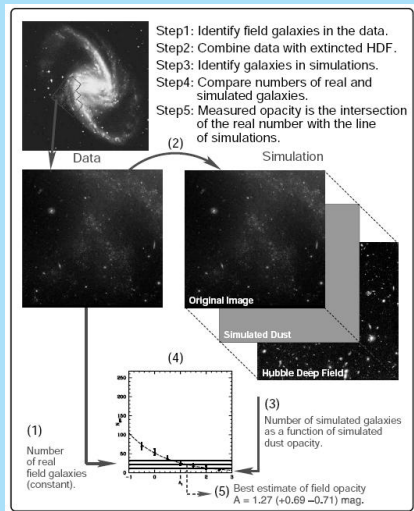been found.

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[8]see www.ipac.caltech.edu/H0kp/.

[9]R.A. González, R.J. Allen, B. Dirch, J.C. Ferguson, D. Calzetta & N.
Panagia, Ap.J. 506, 152 (1998)

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Analysis of Disney et al.
Edge-on galaxies
**Background galaxies**

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Edge-on galaxies
**Background galaxies**
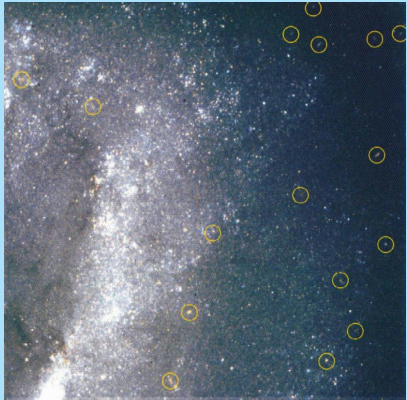
The synthetic field method works as follows. One starts with a set of HST images of nearby galaxies.

This is then compared to images where the HDF has been superposed with various amount of dimming.

The dimming where the same number of galaxies per unit solid angle is found then shows the amount of absorption.



Step1: Identify field galaxies in the data.
Step2: Combine data with extincted HDF.
Step3: Identify galaxies in simulations.
Step4: Compare numbers of real and simulated galaxies.
Step5: Measured opacity is the intersection of the real number with the line of simulations.

(2)

Data                    Simulation

Original Image

Simulated Dust

Hubble Deep Field

(4)

(1)
Number of real field galaxies (constant).

(3)
Number of simulated galaxies as a function of simulated dust opacity.

(5) Best estimate of field opacity
A = 1.27 (+0.69 −0.71) mag.

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**Background galaxies**

Here is the final result from this project[10]:



Top: Average color of background galaxies in observed fields and in HDF (dotted line).

Middle: Number of observed galaxies (filled histogram) and in synthessized fields.

Bottom: Inferred extinction.

---
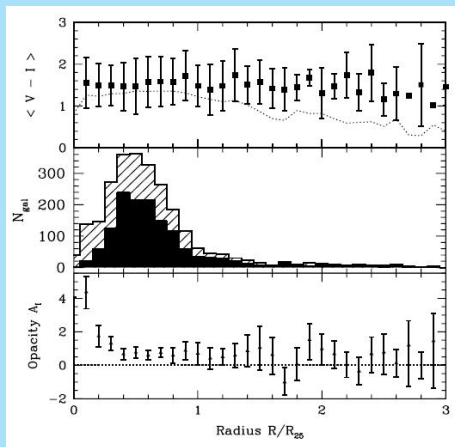
[10]B.W. Holwerda, Ph.D. Thesis; B.W. Holwerda, R.A. Gonzalez, R.J. Allen & P.C. van der Kruit, Ap.J. 129, 1381 (2004)

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# Chemical evolution

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## Abundance gradients

**Bulges** have color gradients (become bluer with radius).

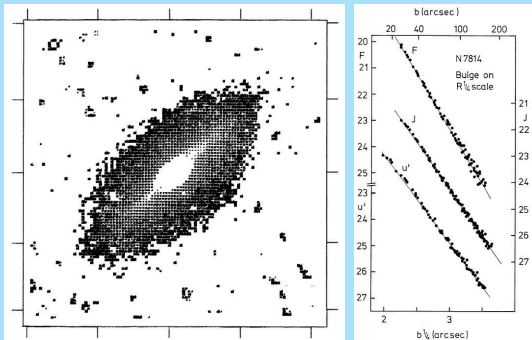This is due to metallicity changes.

For a low [Fe/H] in an old population:

- ▶ The effective temperature of the giant branch is higher
- ▶ There is less line-blanketing
- ▶ The horizontal branch is more extended towards the blue.

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The relation between color and metallicity can be calibrated using the integrated light of Galactic globular clusters.

The range in (U-B),(B-V) in bulges is roughly that in globular clusters.

So the range in metallicity in bulges is 1 - 2 dex in [Fe/H]. }

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There is such a pronounced color gradient in the bulge of NGC 7814[11]



$$\mu_{U'} = 14.87 + 3.32b^{1/4}$$

$$\mu_{J\,opt} = 13.72 + 3.55b^{1/4}$$

$$\mu_{V} = 13.08 + 3.75b^{1/4}$$

$$\mu_{F} = 10.70 + 4.20b^{1/4}$$

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**Disks** have gradients in emission line ratio's in HII regions.

Some prominent emission lines in spectra of HII-regions are the following:

| Ion | Wavelength |
|-----|------------|
| [OII] | 3726/3729 |
| H$\delta$ | 4101 |
| H$\gamma$ | 4340 |
| H$\beta$ | 4861 |
| [OIII] | 4959/5007 |
| H$\alpha$ | 6562 |
| [NII] | 6548/6583 |
| [SII] | 6716/6731 |

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An often used parameter is the "excitation", which is the ratio of the strengths of the [OIII] and H$\beta$ lines.

These are at about the same wavelength, so this ratio is not sensitive to extinction corrections.

The exitation could change due to a number of effects:

▶ Changing dust content and therefore radiation field

▶ Changing stellar temperatures; increasing $T_{\mathrm{eff}}$ gives increasing excitation

▶ Changing abundance because of cooling through O- and N-ions:
   A lower oxygen abundance gives an increased $T_{\mathrm{e}}$ and then we get stronger O-lines; thus [OIII]/H$\beta$ *increases with decreasing metallicity*.

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Detailed studies[a] have shown that the effect of abundance gradients is probably the most important.

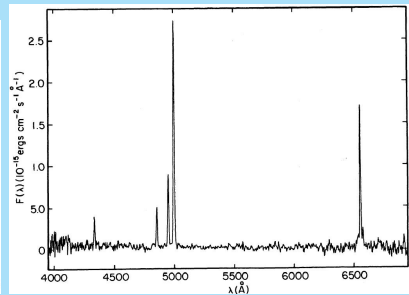As an example we have a detailed look at measurement in M81[b] between 3 and 15 kpc.

────────────────────────

[a]L. Searle, Ap.J. 168, 327 (1973)
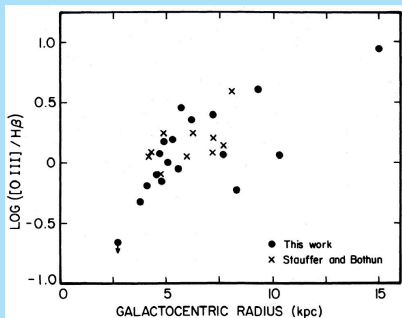[b]D.R. Garnett & G.A. Shields, Ap.J. 317, 82 (1987)

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This is the spectrum of an HII-region at R = 7 kpc.

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This is the spectrum of an HII-region at R = 15 kpc.

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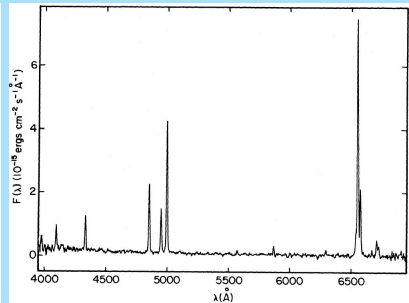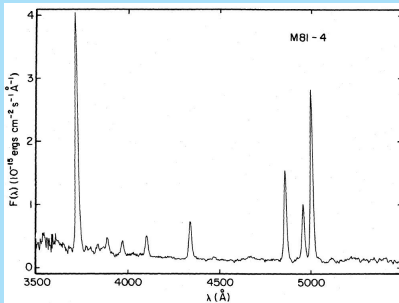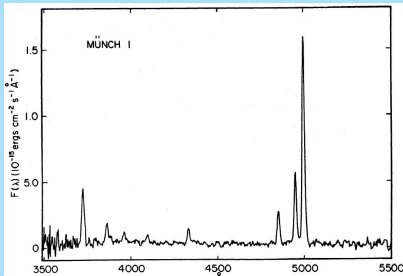
Here we see the gradients in [OIII]/H$\beta$ ratio and the ([OIII]+[OII])/H$\beta$ ratio.

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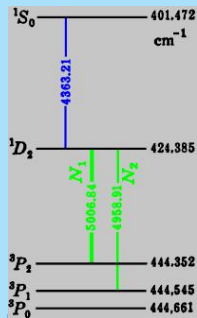Bi-model star formation
Comparison to observations
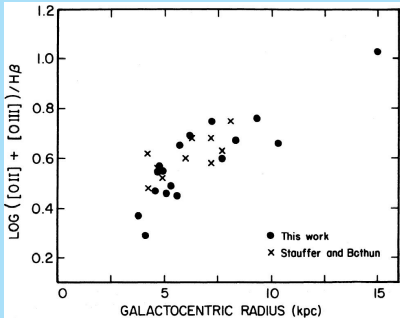
The use of [OIII] and [OII]] has the advantage that two levels of ionisation of the oxygen are taken.
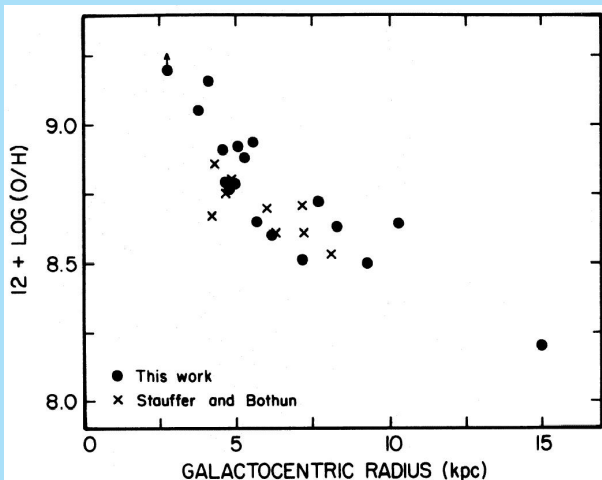
The disadvantage is that the extinction corrections are important.

The line ratio's must be transformed into abundances. The calibration of excitation into abundance can be done in two ways:

• Measure the weak [OIII] line at $\lambda$ 4363 in addition to the lines at $\lambda$ 4959 and 5007. Then lines are measured involving the same level and from this the electron temperature $T_e$ can be calculated. This allows the determination of the oxygen-hydrogen ratio.

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• The second possibility is to calculate full sets of photoionization models of HII regions.

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The result for these measurements in M81 is a gradient of -0.08 dex kpc$^{-1}$ in [O/H].

This is a typical value for spiral disks, including our own.

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# Theory of chemical evolution

Take a volume (either a whole galaxy or a part of it) and define within that volume:

$M_{\mathrm{g}}$ = Mass in gas

$M_*$ = Mass in stars

$M_{\mathrm{Z}}$ = Mass in heavy elements

$Z(t) = M_{\mathrm{Z}}(t)/M_{\mathrm{g}}(t)$ = Abundance

$$y = \frac{\text{Mass injected in new metals}}{\text{Mass locked in long} - \text{lived stars}} = \text{Yield}[12]$$

---

[12]Searle & Sargent, Ap.J. 173,25 (1972)

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The Instantaneous Recycling Approximation (IRA) says that star evolution of heavy stars is instantaneous and that the products are mixed instaneously into the interstellar medium.

Assume the system is closed (no inflow or outflow of gas).

Then the fundamental equations are:

$$\frac{dM_Z}{dt} = y\frac{dM_*}{dt} - Z(t)\frac{dM_*}{dt}$$

$$\frac{dM_g}{dt} = -\frac{dM_*}{dt}$$

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## A. The Simple Model

This assumes that $Z(t=0) = Z_\circ = 0$.

Define

$$x = \frac{M_g(t)}{M_{tot}}$$

The fundamental equations can then be solved to give

$$Z(t) = y \ln \left( \frac{1}{x} \right)$$

The metal abundance of the gas is an increasing function of the gas fraction $x$ and time.

Stars have the abundance of the gas at the time of their birth.

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The fraction of stars at time $t$ with abundance $Z \leq Z_1 (\leq Z(t))$ is:

$$F(Z) = \frac{1 - x_1}{1 - x}$$

$$x_1 = \exp\ -\left(\frac{Z_1}{y}\right)$$

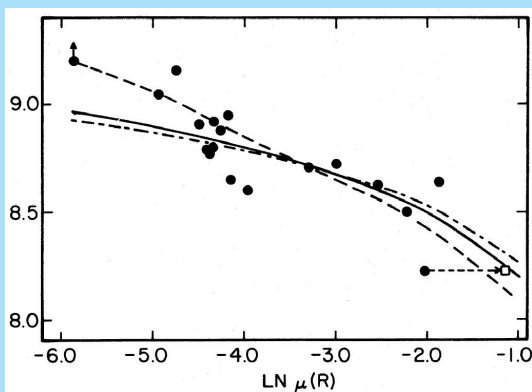So

$$\langle Z \rangle = y \frac{1 - x(1 - \ln x)}{1 - x}$$

Use up all the gas ($x \to 0$), then $\langle Z \rangle \to y$.

So: Abundance of gas $\to \infty$.

The *mean* abundance of stars $\to y$.

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The observations in M81 can be used to test this model.

For that purpose the radius has been replaced by the gas fraction (from the HI and the photometry) $\mu(R)$.

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The thick line shows the
observed distribution
and Simple Model is the
full-drawn line.

The Simple Model
suffers from the G-dwarf
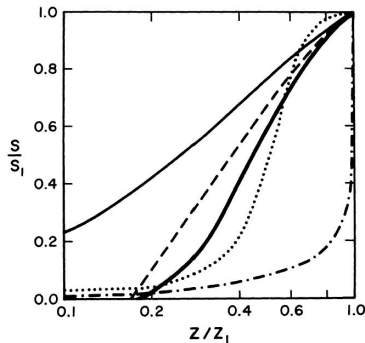problem:
**It predicts far too
many stars of low
metallity.**



*Figure 5* Metallicity distributions. $S/S_1$ is the fraction of G-K dwarfs in the solar neighborhood with metal abundance less than $Z$, where $Z_1$ is the present interstellar abundance (except as noted below). *Heavy line:* schematic representation of the data after removing an estimated dispersion due to observational errors (after Pagel & Patchett 1975). *Light solid line:* the "simple model" [Equation (3)]. *Dashed line:* effect of a finite initial abundance, $Z_0 = 0.17\,Z_1$. *Dash-dotted line:* an infall model [Equation (4)]. *Dotted line:* the infall model with a log gaussian distribution of $Z$ at all times, with $\sigma(\log Z) = 0.2$. In this case, $Z_1$ is the value at which $S/S_1 \approx 1$ (cf Tinsley 1975a).

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The simple model predicts that of the G-dwarfs in the solar neighborhood more than 40% should have a metallicity less than 0.2 of solar.

This fundamental problem was first noted by Maarten Schmidt[13].

There are two general ways to cure this; namely a non-zero abundance in the gas at the beginning or an extended inflow of unenriched material.

We will now explore these two options.

---

[13]M. Schmidt, Ap.J. 137, 758 (1963)

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## B. The Extended Simple Model.

The assumptions are the same as in the simple model, except that $Z_\circ \neq 0$.

This is also known as Prompt Initial Enrichment (PIE).

Then everywhere replace $y$ with $y + Z_\circ$ and the equations look the same.

The solution then is

$$Z(t) = Z_\circ + y \ln \left( \frac{1}{x} \right)$$

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So, now when we use up all gas, we get

Abundance of gas $\rightarrow \infty$.

Mean abundance of stars $\rightarrow y + Z_\circ$.

Because the metallicity of the gas is initially finite, there are (much) fewer metal-poor stars.

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The Prompt Initial
Enrichment Model now
is the dashed line.

This is a better
representation of the
observed distribution.

(The thick line was the
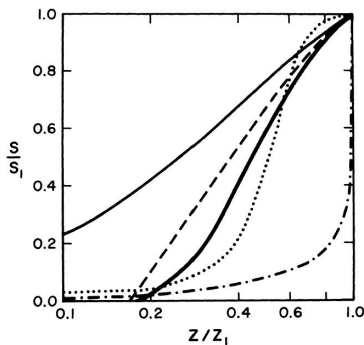observed distribution
and the full-drawn line
the simple model) .



Figure 5 Metallicity distributions. $S/S_1$ is the fraction of G-K dwarfs in the solar neigh-borhood with metal abundance less than $Z$, where $Z_1$ is the present interstellar abun-dance (except as noted below). *Heavy line*: schematic representation of the data after removing an estimated dispersion due to observational errors (after Pagel & Patchett 1975). *Light solid line*: the "simple model" [Equation (3)]. *Dashed line*: effect of a finite initial abundance, $Z_0 = 0.17 Z_1$. *Dash-dotted line*: an infall model [Equation (4)]. *Dotted line*: the infall model with a log gaussian distribution of $Z$ at all times, with $\sigma(\log Z) = 0.2$. In this case, $Z_1$ is the value at which $S/S_1 \approx 1$ (cf Tinsley 1975a).

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## C. Inflow Model.

Assume an inflow $f(t)$ of unprocessed material.

This means that there is less gas in the beginning compared to the simple model and the enrichment then proceeds much faster and therefore decreases the predicted number of G-dwarfs.

The second fundamental equation becomes

$$\frac{dM_{\mathrm{g}}}{dt} = -\frac{dM_*}{dt} + f(t)$$

This model cannot be solved analytically in the general case, but it can be done fore the extreme inflow model, where $M_{\mathrm{g}} = \text{constant}$.

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Define

$$\mu = \frac{M_*(t)}{M_{\mathrm{g}}}$$

Then

$$Z(t) = y\left\{1 - \exp\left(-\mu\right)\right\}$$

It can then be found that

$$F(Z) = \frac{\mu}{\mu_1}$$

$$\langle Z \rangle = y - \frac{y}{\mu} + \frac{y}{\mu}\exp\left(-\mu\right)$$

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If we now use up all gas, we get

$\mu \rightarrow \infty$ and $\langle Z \rangle \rightarrow y$.

Abundance of gas $\rightarrow y$.

Mean abundance of stars $\rightarrow y$.

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The extreme infall model
is the dash-dotted line.

(The thick line wass the
observed distribution,
the full-drawn line
simple model and the
dashed line the Prompt
Initial Enrichment
Model.)



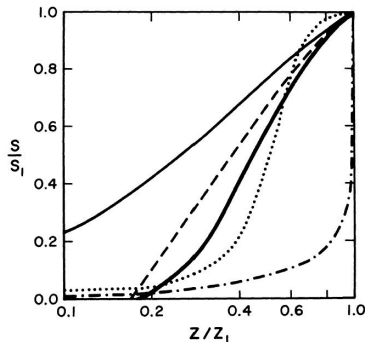*Figure 5* Metallicity distributions. $S/S_1$ is the fraction of G-K dwarfs in the solar neighborhood with metal abundance less than $Z$, where $Z_1$ is the present interstellar abundance (except as noted below). *Heavy line:* schematic representation of the data after removing an estimated dispersion due to observational errors (after Pagel & Patchett 1975). *Light solid line:* the "simple model" [Equation (3)]. *Dashed line:* effect of a finite initial abundance, $Z_0 = 0.17 Z_1$. *Dash-dotted line:* an infall model [Equation (4)]. *Dotted line:* the infall model with a log gaussian distribution of $Z$ at all times, with $\sigma(\log Z) = 0.2$. In this case, $Z_1$ is the value at which $S/S_1 \approx 1$ (cf Tinsley 1975a).

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The extreme inflow model is much too extreme in that it now predicts too few metal-poor stars.

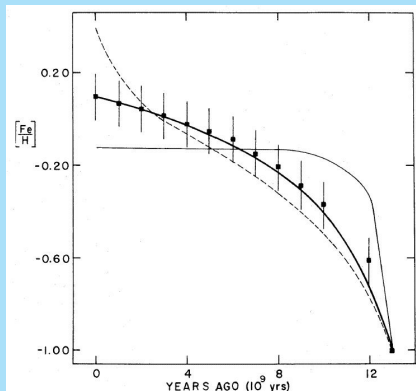So, $M_{\mathrm{gas}}$ must have decreased with time.

The dotted line in the previous figure is an example of an adapted infall model.

The inflow is possibly seen in our Galaxy as the high-velocity clouds.

The best fit can be found for the Solar Neighborhood with a combination of prompt initial enrichment and inflow.

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When the time is made explicit (e.g. by assuming that the SFR is constant) this model can reproduce the metallicity - age relation[14].



_____

[14]B.A. Twarog, Ap.J. 242, 242 (1980)

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## D. Simple Model with Bells and Whistles.[15]

This term is now used for any model that relaxes the assumptions of the simple model, but was used originally for models with outflow of processed material.

Let there be an outflow of processed material $g(t)$.

Then the fundamental equations become

$$\frac{dM_Z}{dt} = y\frac{dM_*}{dt} - Z(t)\frac{dM_*}{dt} - Z(t)g(t)$$

$$\frac{dM_g}{dt} = -\frac{dM_*}{dt} - g(t)$$

---

[15] J.R. Mould, P.A.S.P. 96, 773 (1984)

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For an illustrative case that can be solved analytically, take

$$g(t) = \alpha \frac{dM_*}{dt}$$

Then we have the fundamental equations back with $y$ replaced with an *effective* yield

$$y' = \frac{y}{1 + \alpha}$$

The solution is then

$$Z(t) = \frac{y}{1 + \alpha} ln\left(\frac{1}{x}\right)$$

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Use up all gas, then:

Abundance of gas $\rightarrow \infty$.

Mean abundance of stars $\rightarrow y' = y/(1 + \alpha)$.

For elliptical galaxies there is a mass - metallicity relation[16].
This can be explained if elliptical galaxies have (had) outflow of
processed material, which must haven been more pronounced in
smaller systems.

---

[16] J.R. Mould, P.A.S.P. 96, 773 (1984)

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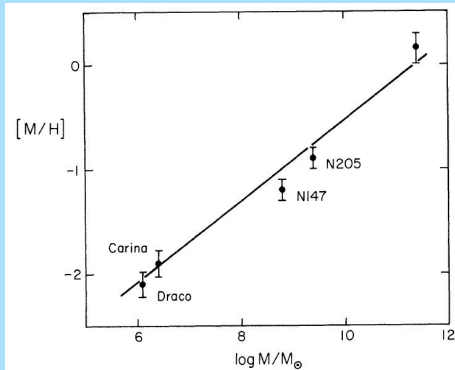Bi-model star formation
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Fig. 2—A mass-metallicity relation for elliptical galaxies. The unlabeled point shows the metallicity inferred for the brightest ellipticals from integrated light models.
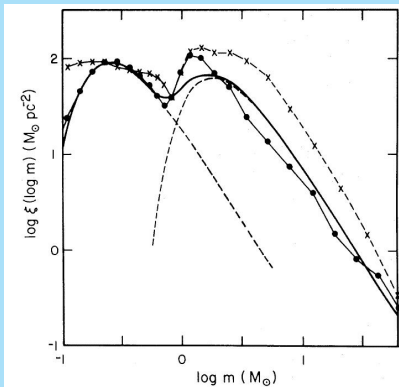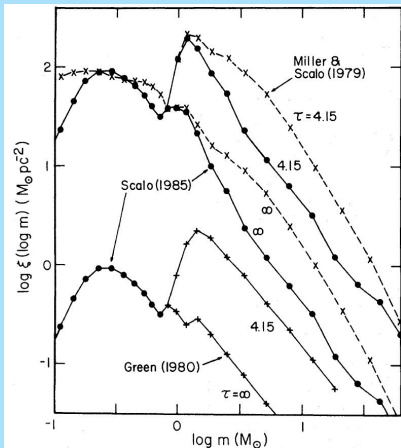
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## Bi-modal star formation

It is possible to relax the continuity constraint in the determination of the IMF and assume bi-modal star formation[17].

This is based on the idea of two modes of star formation, that are independent.

This continuity constraint can be relaxed and that also is a possible solution of the G-dwarf problem, since it uncouples the formation of lighter stars from the enrichment by the massive stars.

---

[17]R.B. Larson, Mon.Not.R.A.S. 218, 409 (1986)

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If $C$ is the number of stars formed $(\log M)^{-1}$ pc$^{-2}$ Gyr$^{-1}$:

$$C(\log M, t) = SFR_1(t) \cdot IMF_1(\log M) + SFR_2(t) \cdot IMF_2(\log M)$$

$$IMF_{\mathrm{k}}(\log M) = 2.55 M_{\mathrm{k}} M^{-2} \exp\left[-\left(\frac{M_{\mathrm{k}}}{M}\right)^{3/2}\right]$$

$$SFR_{\mathrm{k}}(t) = A_{\mathrm{k}} \exp\left(-\frac{t}{\tau_{\mathrm{k}}}\right)$$

- Low mass: $\tau_1 = \infty$, $M_1 = 0.30 M_\odot$, $A_1 = 1.85 M_\odot \mathrm{pc}^{-2}\mathrm{Gyr}^{-1}$

- High mass: $\tau_2 = 3.4$ Gyr, $M_2 = 2.2 M_\odot$, $A_2 = 41 M_\odot \mathrm{pc}^{-2}\mathrm{Gyr}^{-1}$

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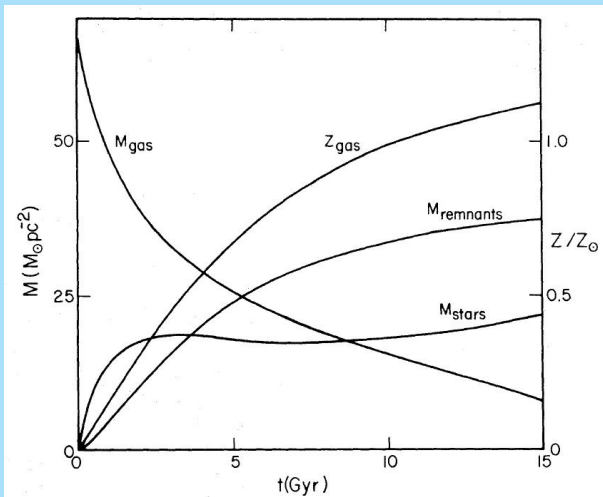Comparison to observations

Effects of bi-modal star formation:

• This explains in a natural way the occurrence of two types of associations; the O-associations having OB-stars and the T-associations having only T Tauri stars.

• A smaller amount of mass has gone into long-lived stars per unit luminosity of newly formed stars during the whole history.
This solves the problem of the gas consumption time-scale (why do all galaxies use their gas in another Hubble time or less?).

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• More mass is in invisible remnants of massive stars (white dwarfs, etc.).
For $M_{\mathrm{remnant}} = 0.38 + 0.15 M_*$ this adds up to about 3/4 of the mass density.
This solves the local missing mass problem (Oort limit), but is only compatible with observations if the fading time is less than 10 Gyr.

• Rapid early increase in [Fe/H] combined with low relative SR in low-mass stars. This solves the G-dwarf problem of the simple model for chemical evolution.

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## Comparison to observations

▶ Abundance gradients in bulges:
   This results from a change in the effective yield with radius
   due to changing escape rates of processed gas.

▶ Overall abundances of ellipticals:
   There is a correlation of [Fe/H] with $M_{\rm V}$, which follows if for
   more massive systems the gas has more difficulty to escape.

▶ Disk abundance differences between galaxies:
   Earlier types have higher metallicities, because more gas has
   been used in star formation.

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Abundance gradients
Theory of chemical evolution
Bi-model star formation
**Comparison to observations**

▶ Gas abundance gradients in disks:
  This results from radial gradient in relative gas consumption
  and content.

▶ Stellar abundance gradients in disks:
  No gradients should result if most of the gas is used up (the
  mean stellar abundance is then equal to the yield); at least it
  should be smaller than in the gas.