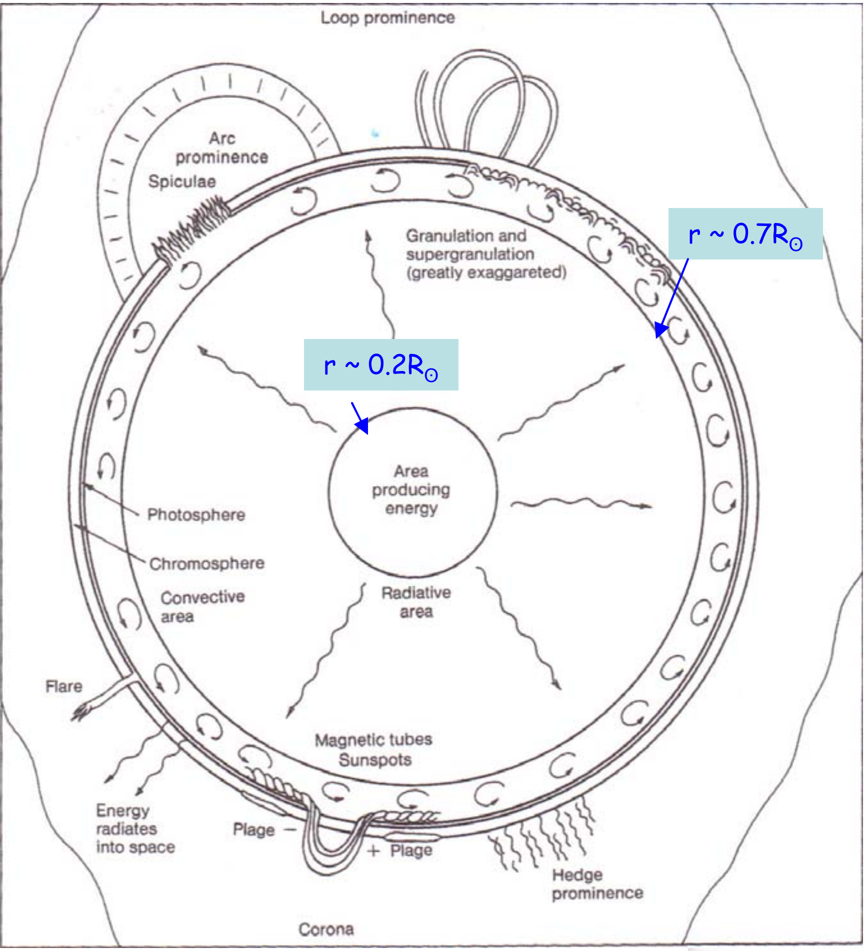
AY 20 Fall 2010

The Solar Cycle
Interstellar Dust

Reading: Carroll & Ostlie, Chapter 11.3, Chapter 12.1



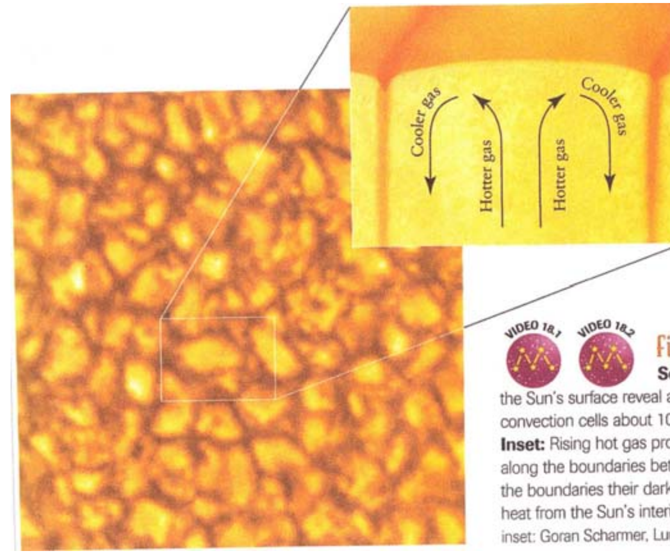
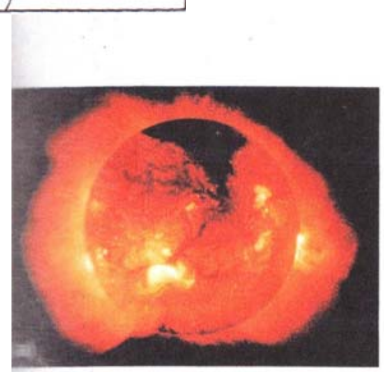


Figure 18-10 R I V U X G
Solar Granulation High-resolution photographs o the Sun's surface reveal a blotchy pattern called granulation. Granules are convection cells about 1000 km (600 mi) wide in the Sun's photosphere. **Inset:** Rising hot gas produces bright granules. Cooler gas sinks downward along the boundaries between granules; this gas glows less brightly, giving the boundaries their dark appearance. This convective motion transports heat from the Sun's interior outward to the solar atmosphere. (MSFC/NASA inset: Goran Scharmer, Lund Observatory)

Solar structure
Reading: C & O §11.2
"descriptive"



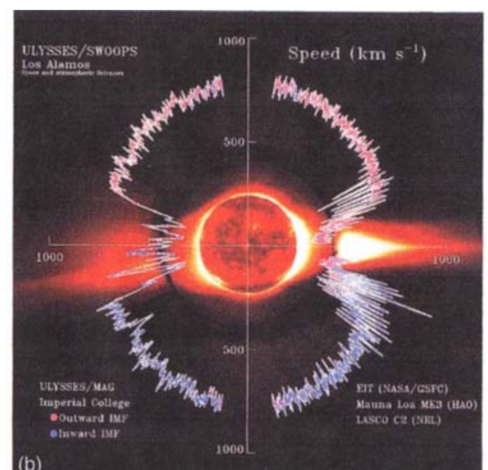


FIGURE 11-24 (a) An X-ray image of the Sun, in false color, taken by the *Yohkoh* satellite. The large, dark area (corresponding to a cooler, less dense region) is a coro nal hole. (b) A composite image of the solar wind and corona, in false color, with additional information on the solar magnetic field and speed of the solar wind. Data and images were taken by the *Ulysses* and *SOHO* spacecraft (ESA/NASA missions) and correspond to the 1994 period of sunspot minimum.

Solar Wind: from expansion of corona (Parker)

Solar corona: high T, ionized gas ≡ plasma

High conductivity → isothermal

Hydrostatic equilibrium: $dP/dr = -GM_\odot \rho/r^2$ (here $M_r \approx M_\odot$)

Completely ionized gas: number density of protons $n_p \approx \rho/m_p$

(since $n_p \approx \rho/m_H$)

From ideal gas law $P = 2nkT \therefore d/dr(2nkT) = -GM_\odot \rho/r^2$

$\therefore dn/dr = -GM_\odot/2kT \times n_p m_p/r^2$

Integrating → $n(r) = n_0 e^{-\lambda(1-r_0/r)}$ $\lambda \equiv GM_\odot m_p/2kTr_0$; $n = n_0$ at $r = r_0$

$\therefore P(r) = P_0 e^{-\lambda(1-r_0/r)}$ and $P_0 = 2n_0kT$

limiting values for P by adopting $r_0 = 1.4R_\odot$, $T = 1.5 \times 10^6$K, $n_0 = 3 \times 10^{13}$ m^{-3}

$\therefore \lambda = 5.5$, $n(\infty) \approx 1.2 \times 10^{11}$ m^{-3} and $P(\infty) \approx 5 \times 10^{-6}$ N m^{-2}

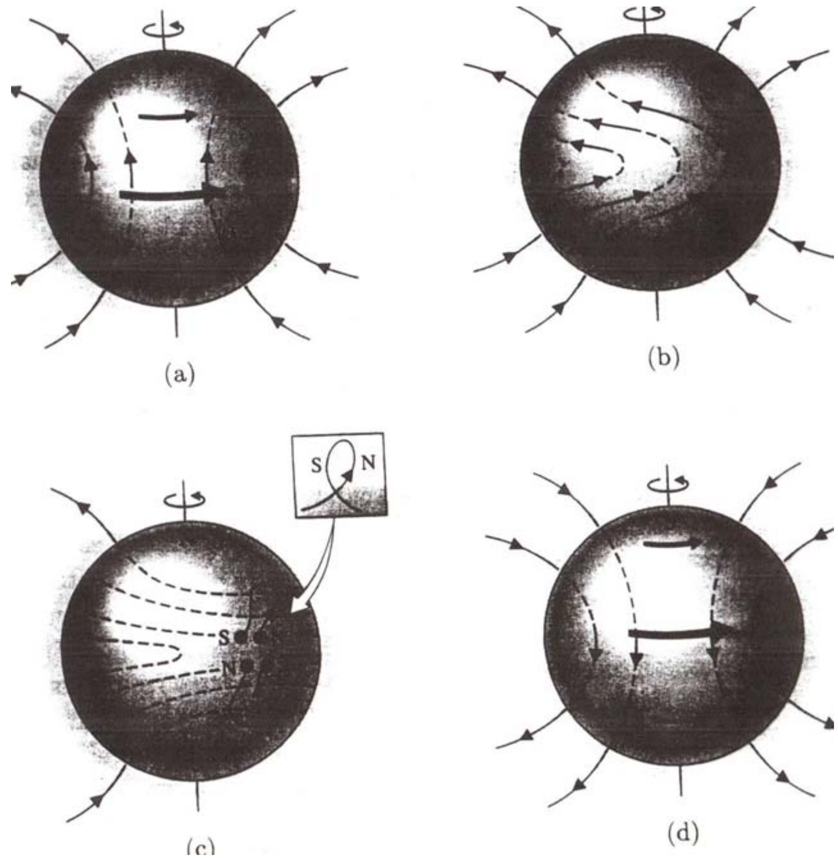
For ISM: $n \sim 3 \times 10^5$ m^{-3} and $P \sim 3 \times 10^{-14}$ N m^{-2}

$\therefore$ material must be moving outward from Sun = solar wind

assumption of hydrostatic equilibrium must be invalid

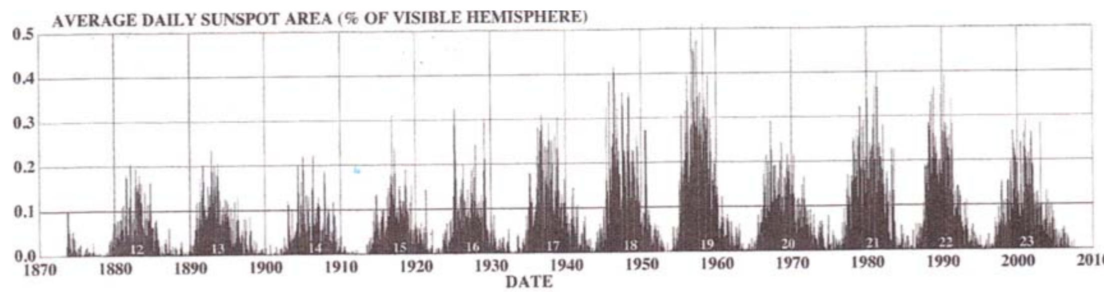
Solar magnetic field implied by coronal holes (X-ray emission) and sunspots as well as by comets

- Field due to electric currents in conducting plasma of convection zone (outer 30% of Sun
- Modeled as a magnetic dynamo by Babcock (1961). Generally successful; but detailed MHD treatment required.
- Initially field poloidal (a). Field lines "frozen in" gas and dragged by Sun's differential rotation (b); turbulence twists lines into "ropes" – rise to surface as sunspots (c)
- Twisting starts at high latitudes, continues to lower. Cancels at equator since polarity of field in lead sunspots ≡ polarity of original of field (opposite in the two hemispheres)
- Cycle of migration of groups in 11 yrs. When complete, poloidal field re-established – with *opposite* polarity (d) →



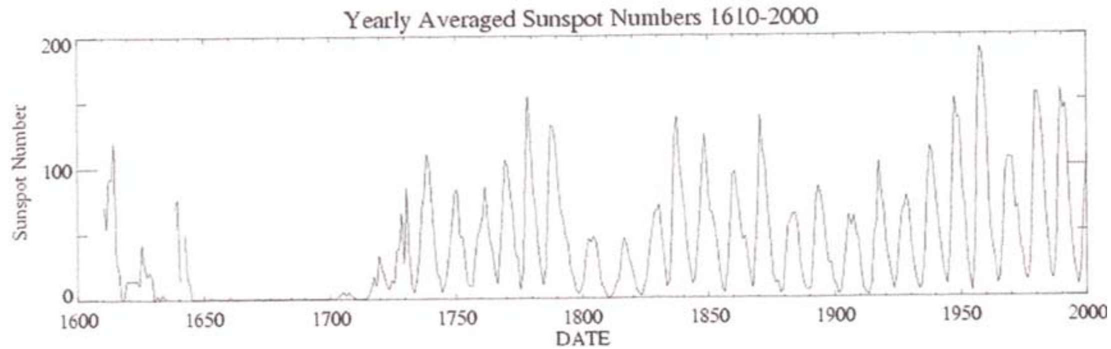
Solar Cycle

- Variation of number of sunspots with time



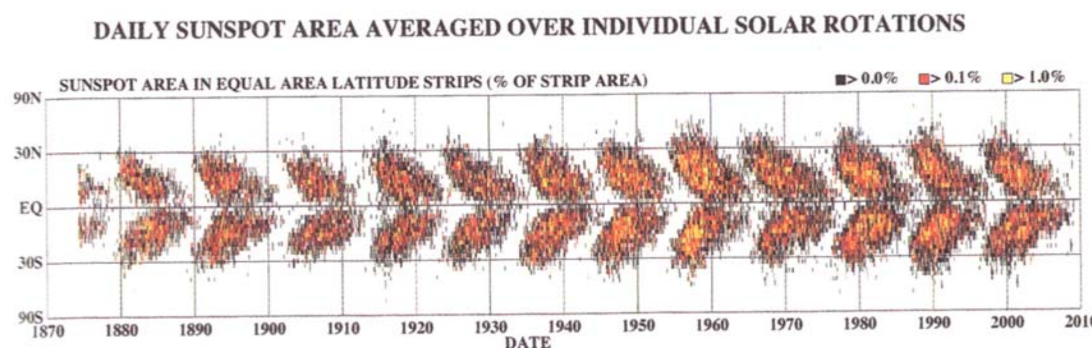
(a)

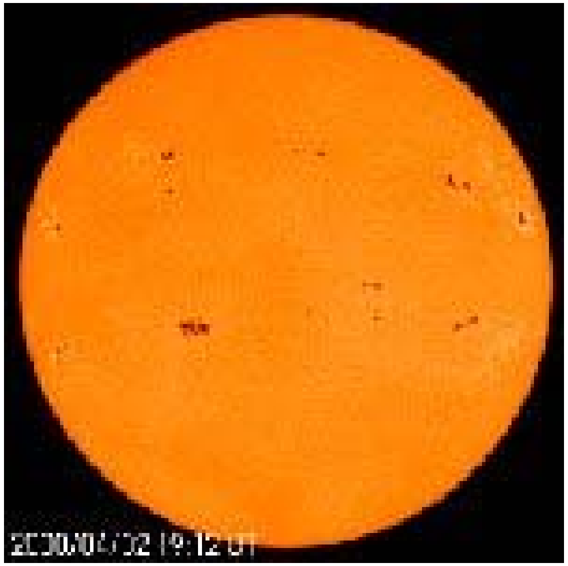
- Yearly average number of sunspots. Minimum between 1645 – 1715 = Maunder Minimum
- Little Ice age for Earth



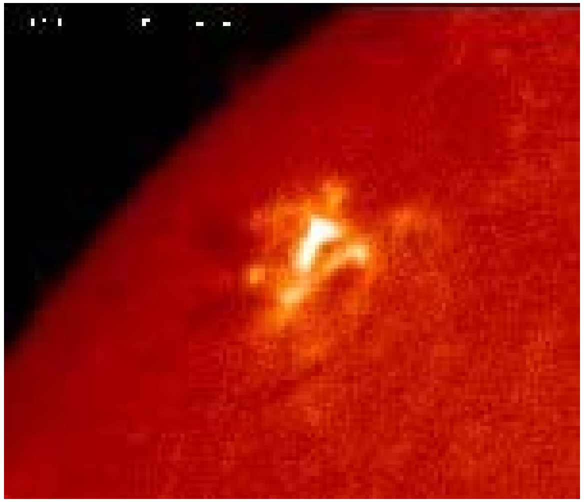
(b)

- Butterfly diagram
- Twisting of magnetic field lines Fig 11:37 C&O

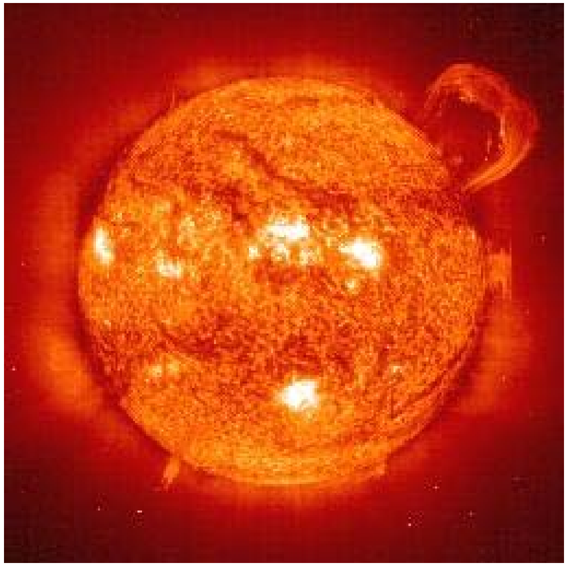




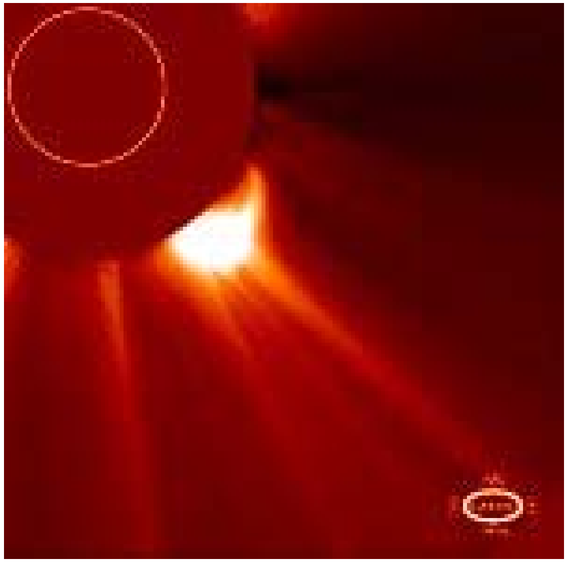
sunspots



flare SOHO



prominences

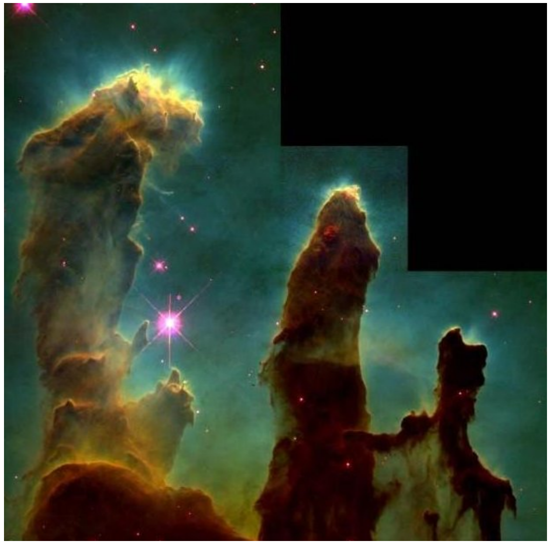


Interstellar Medium – the beginning & the end – and everything in between

- ISM -the material - gas and dust - between stars
- Origin of stars
- Processed material from stars returned to ISM via stellar winds, ejection of stellar envelopes, novae, planetary nebulae, supernovae
- Dynamics, structure, and evolution of Milky Way, other galaxies involves ISM
- ISM a laboratory for exotic experiments
- Everything we've learned so far applies: fundamental physics and chemistry, radiative transfer, hydrodynamics, magnetohydrodynamics…
- And it has annoying effects too

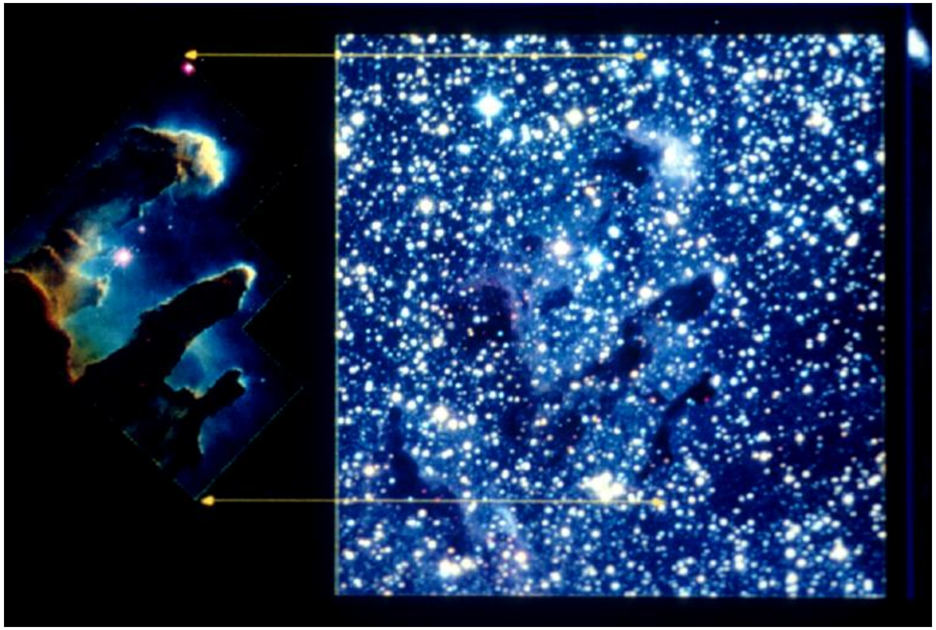
Interstellar Medium & Extinction

AAT



Hubble

European Southern Observatory ESO



Calar Alto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Interstellar Extinction

Cluster survey by Trumpler (1930) → star's radiation m_λ, decreased by intervening material (extinction)

distance modulus $m_\lambda - M_\lambda = 5\log d - 5$

To account for extinction: $(m_\lambda - A_\lambda) - M_\lambda = 5\log d - 5$

$\therefore\ m_\lambda = M_\lambda + 5\log d - 5 + A_\lambda$ (d in pc, A_λ extinction in mags)

Extinction caused by dust particles = obscuration due to scattering or absorption of radiation (λ-dependent)

scattering ≡ "reflected"

absorption followed by re-emission at different λ's

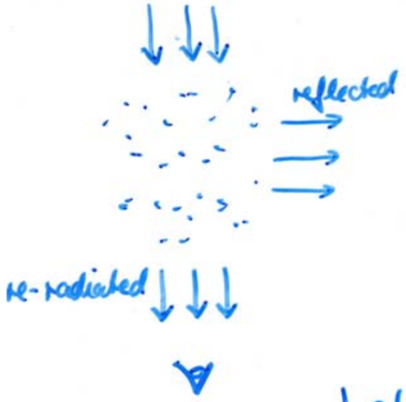
Wien Law: $\lambda_{max} T = 0.29$

ISM: T ~ 10-20K ∴ λ_{max} ~ 300 -150 μm

near hot star: T_* ~ 20,000K, λ_{max} ~ 1450 Å

→ UV radiation re-radiated in IR

Average Extinction in plane of Milky Way = 2^m/kpc



EXTINCTION DEPENDS ON λ, τ, n WHERE n IS NUMBER DENSITY OF DUST GRAINS

$$I_\lambda = I_{\lambda,0}\, e^{-\tau_\lambda}$$

$$m_1 - m_2 = -2.5 \log(F_1/F_2)$$

Let $m_{\lambda,0}$ = apparent magnitude real
m_λ = " " after extinct'n

$$\Delta m = m_\lambda - m_{\lambda,0} = -2.5 \log(F_\lambda/F_{\lambda,0}) = -2.5 \log e^{-\tau_\lambda} = A_\lambda$$

$$\therefore A_\lambda = 2.5\,\tau_\lambda \log e = 1.086\,\tau_\lambda$$

$\therefore$ OPTICAL DEPTH IN LINE OF SIGHT ~ CHANGE IN MAGNITUDE FROM EXTINCTION

$\tau_\lambda = \int_0^s \kappa_\lambda \rho\, ds$ THROUGH 'CLOUD' SIZE S

I FALLS OFF BY e^{-1} OVER DISTANCE $l = 1/\kappa_\lambda \rho = 1/n\sigma_\lambda$

σ_λ = SCATTERING X-SECTION $\quad \therefore \tau_\lambda = \int_0^s n_d(s')\,\sigma_\lambda\, ds'$

$n_d(s')$ = NUMBER DENSITY OF SCATTERING GRAINS

$\therefore$ FOR CONSTANT σ, $\tau_\lambda = \sigma_\lambda \int_0^s n_d(s')\, ds' = \sigma_\lambda N_d$

N_d = DUST COLUMN DENSITY ← 

$\therefore A_\lambda \sim \tau_\lambda \sim N_d$ (const σ_λ)

$\therefore$ EXTINCTION $\propto$ NUMBER OF GRAINS IN LINE OF SIGHT

MIE THEORY FOR DUST PARTICLES:

ASSUME PARTICLES SPHERICAL, RADIUS a

$\therefore$ GEOMETRICAL CROSS-SECTION $\sigma_g = \pi a^2$

EXTINCTION COEFFICIENT $= Q_\lambda$ (COMPOSITION DEPENDENT)

$Q_\lambda = \frac{\sigma_\lambda}{\sigma_g}$ $\qquad \sigma_\lambda =$ SCATTERING CROSS-SECTION

SIMPLISTICALLY, SINCE $Q_\lambda = \sigma_\lambda / \sigma_g$

Later class: Ay 102:

DEFINE $x = 2\pi a/\lambda$, $Q_\lambda \Rightarrow$ SERIES EXPANSION IN x

$\Rightarrow$ FOR PARTICLES OF SIZE COMPARABLE TO λ

$x \gtrsim 1$ AND $Q_\lambda \sim a/\lambda$

$\therefore \sigma_\lambda = Q_\lambda \sigma_g \propto \lambda^{-1}$, for constant a $\qquad \sigma_\lambda \propto 1/\lambda$ $\quad$ Mie scattering

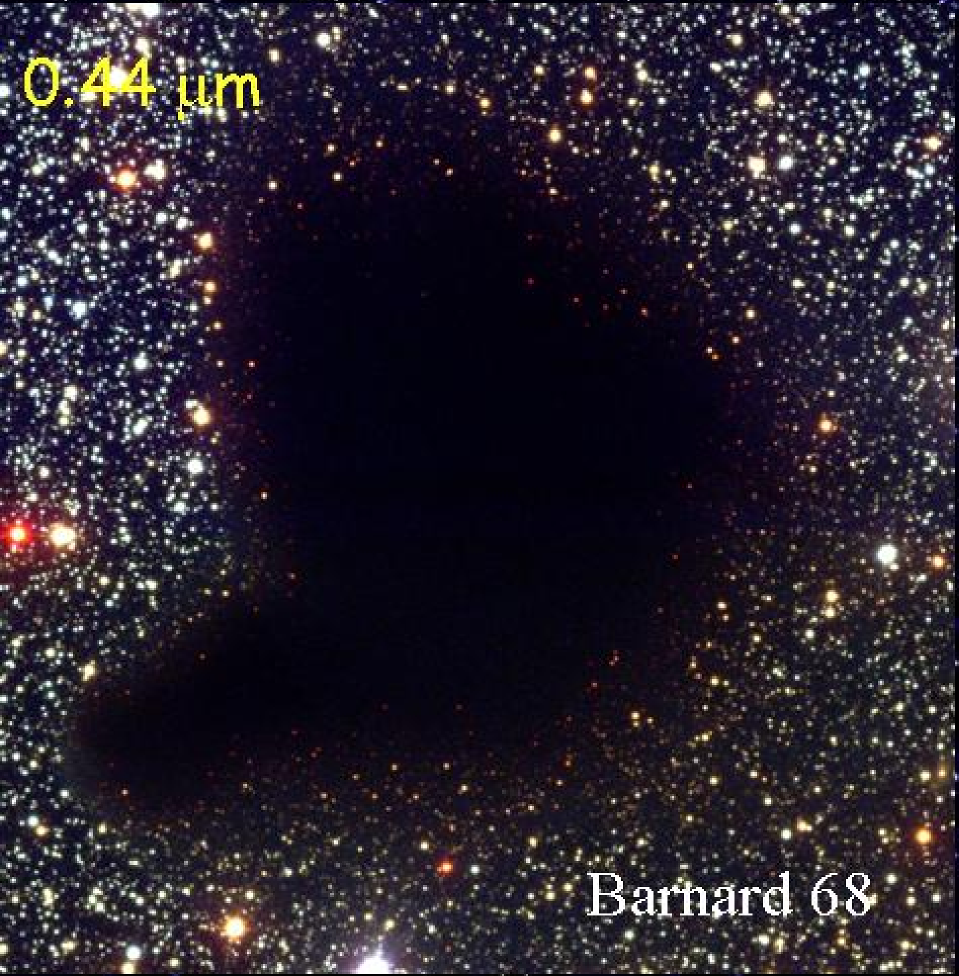
$\because$ IF $\lambda \gg a$, $Q_\lambda \rightarrow 0$; IF $\lambda \ll a$ $Q_\lambda \rightarrow$ CONST.

AND $\sigma_\lambda =$ const.$a^2 \propto a^2$ $\quad$ Rayleigh Scattering

$\therefore$ EXTINCTION DEPENDENT ON SIZE OF PARTICLES/GRAINS (FOR CONSTANT COMPOSITION)

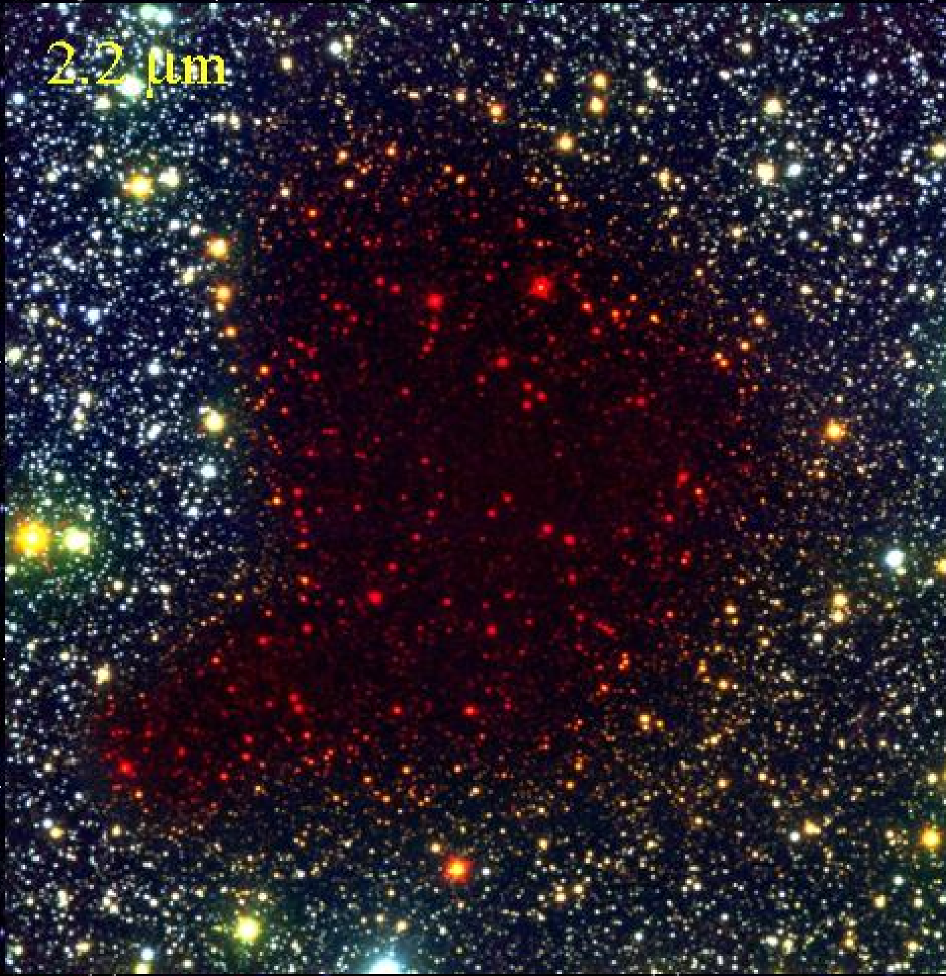
$\therefore$ EXTINCTION MUCH LESS AT LONG WAVELENGTHS : RADIATION AT IR, MM, CM WAVELENGTHS LESS DIMINISHED

Less extinction at longer wavelengths



VLT (BVI)

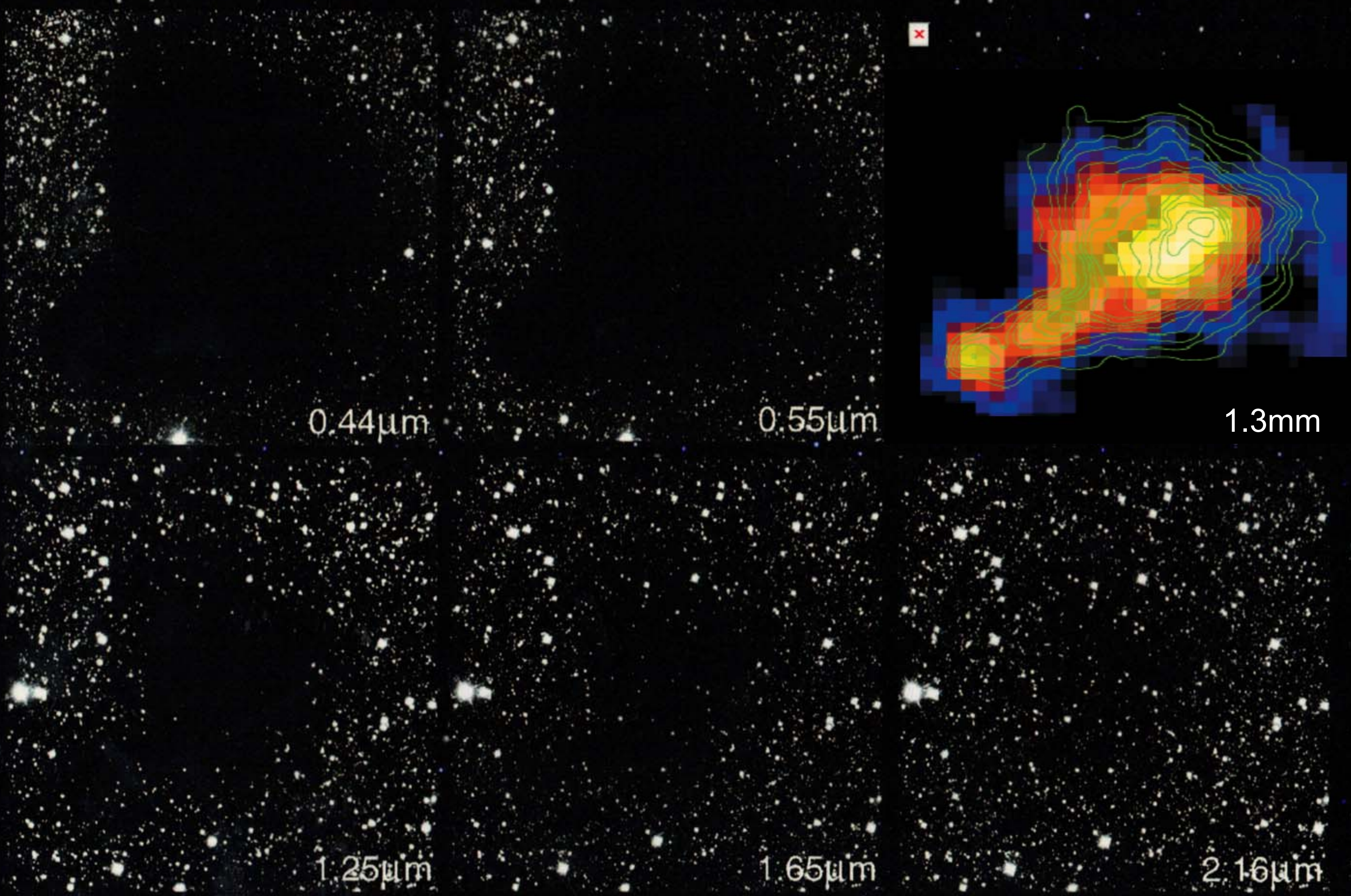
optical image



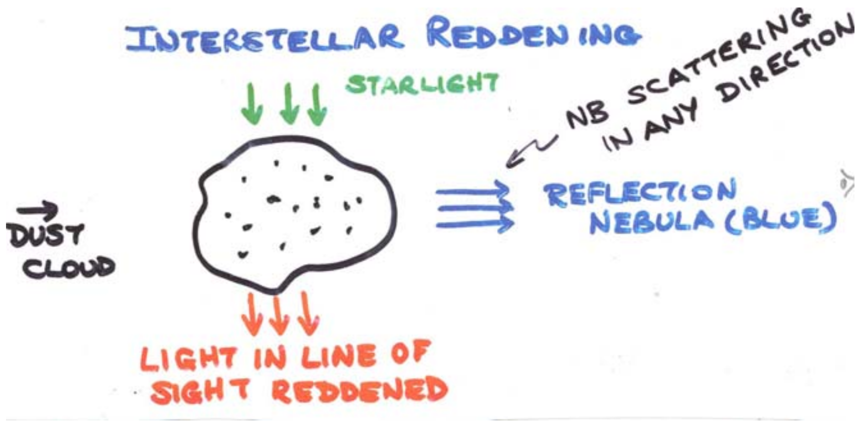
VLT + NTT (BIK)

infrared image

Peering into the darkness



Alves, Lada & Lada 2003



"red" ~ 8000Å

"blue" ~ 3000Å

Mie scattering: $\sigma_\lambda \propto 1/\lambda$ $\therefore$ blue photons scattered more than red

$\therefore$ emergent radiation in line of sight redder than when emitted by star

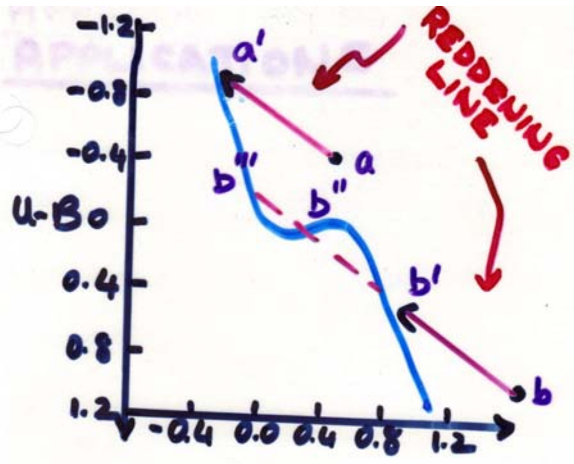
AND, if absorbed and re-radiated, emerges at much longer λ

In presence of dust, T_{eff} from observations much lower than at star

$$A_\lambda = 1.086\tau_\lambda \sim \tau_\lambda = N_d,$$ *column* density

When $\lambda \gg a \rightarrow$

Rayleigh scattering $\sigma_\lambda \propto \lambda^{-4}$ = very strong dependence



- REDDENING DISTORTS DERIVED STELLAR PROPERTIES
  e.g. DISTANCE MODULUS, T_{eff}, since λ_{max} SHIFTED (WIEN'S LAW)
- CAN 'DE-REDDEN' USING COLOR-COLOR DIAGRAM

REDDENING MEANS MEASURED FLUXES PUT STARS AT POSITION a RATHER THAN a'

COLOR EXCESS = $(B-V)$ − $(B-V)_0$ = E_{B-V}

(B−V) MEASURED; $(B-V)_0$ INTRINSIC = $M_B - M_V$

∴ TRUE $(B-V)_0$ = MEASURED $(B-V) - E_{B-V}$

e.g. CASE a: $B-V = 0.4$, $(B-V)_0 = 0$, $E_{B-V} = -0.4$

[FOR CASE b, SAME EXCESS IF IN SAME CLUSTER ONLY]

SINCE $V = M_V + 5\log d - 5 + A_V$, $B = M_B + 5\log d - 5 + A_B$

$$B-V = M_B - M_V + A_B - A_V = (B-V)_0 + A_B - A_V$$

$$\therefore E_{B-V} = (B-V) - (B-V)_0 = A_B - A_V$$

EMPIRICALLY $A_V / E_{B-V} \simeq 3 = R$

$$\therefore E_{B-V} = 3A_V$$

∴ COLOR EXCESS ≡ VISUAL EXTINCTION