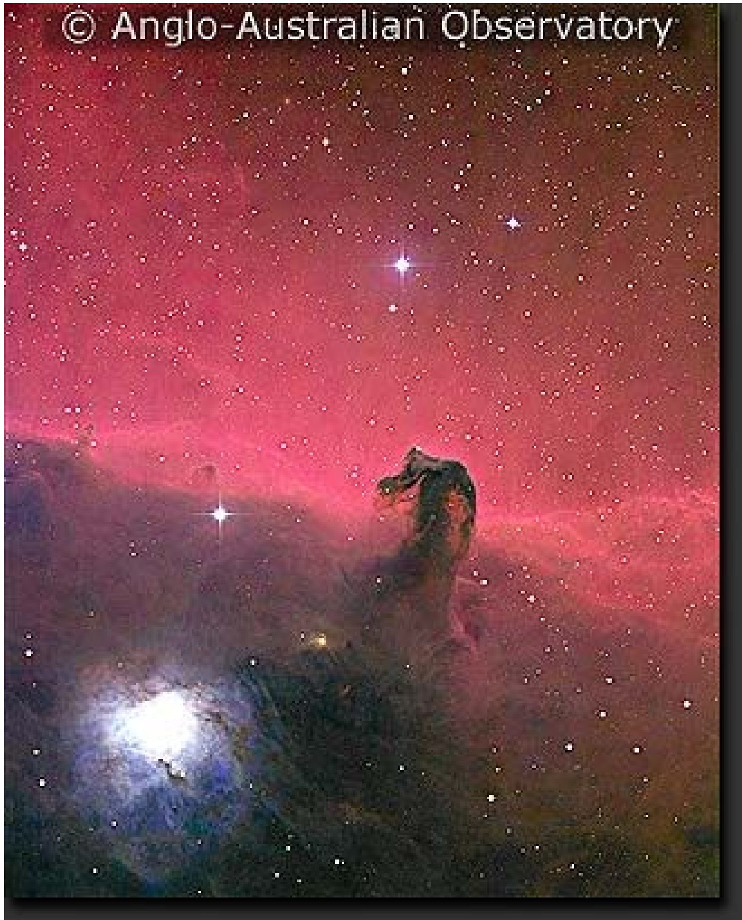
The Physics of the Interstellar Medium



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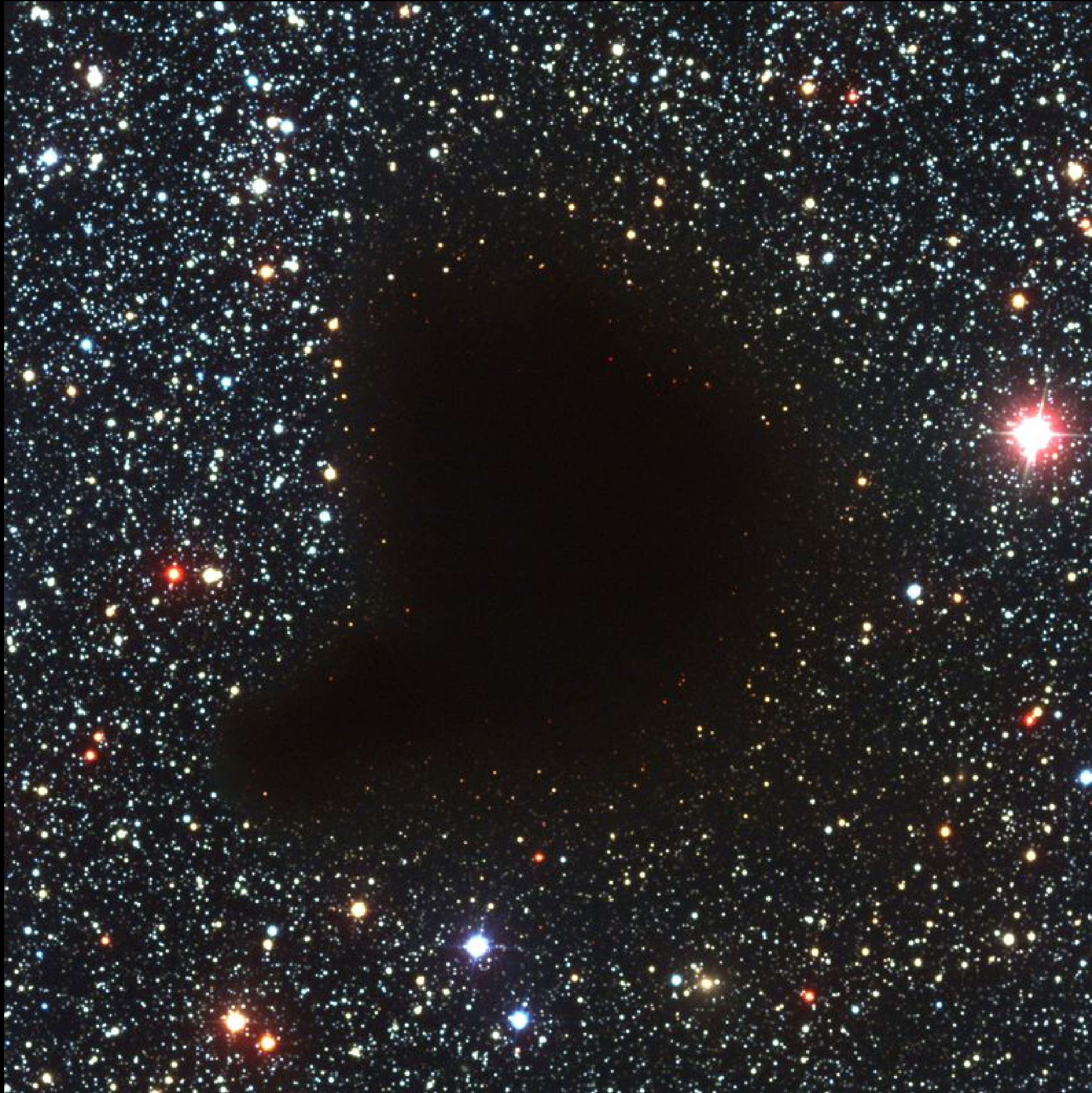
Matter between stars

- Average distance between stars in solar neighbourhood: 1 pc = 3 x 10^{13} km, average star diameter: 10^6 km
- => part of space occupied by stars: $(10^6 / 3 \times 10^{13})^3$ = about 10^{-22}
- Upper limit for matter other than known stars
  – Oort limit = total matter density in galactic plane from gravitational acceleration of stars = 0.1 M_{Sun} pc^{-3}
  – Density of known stars = 0.05 M_{Sun} pc^{-3}
  – Upper limit for IS density = 10^6 atoms m^{-3}

Matter between stars

- Observational evidence for matter between stars (up to 1930s):
  - Optical images: dark clouds and diffuse bright nebula
  - Photometry: Interstellar extinction and reddening
  - Spectroscopy: IS absorption lines in stellar spectra: stationary in spectroscopic binary spectra, different doppler shift, strength increasing with distance



The "Black Cloud" B68
(VLT ANTU + FORS1)

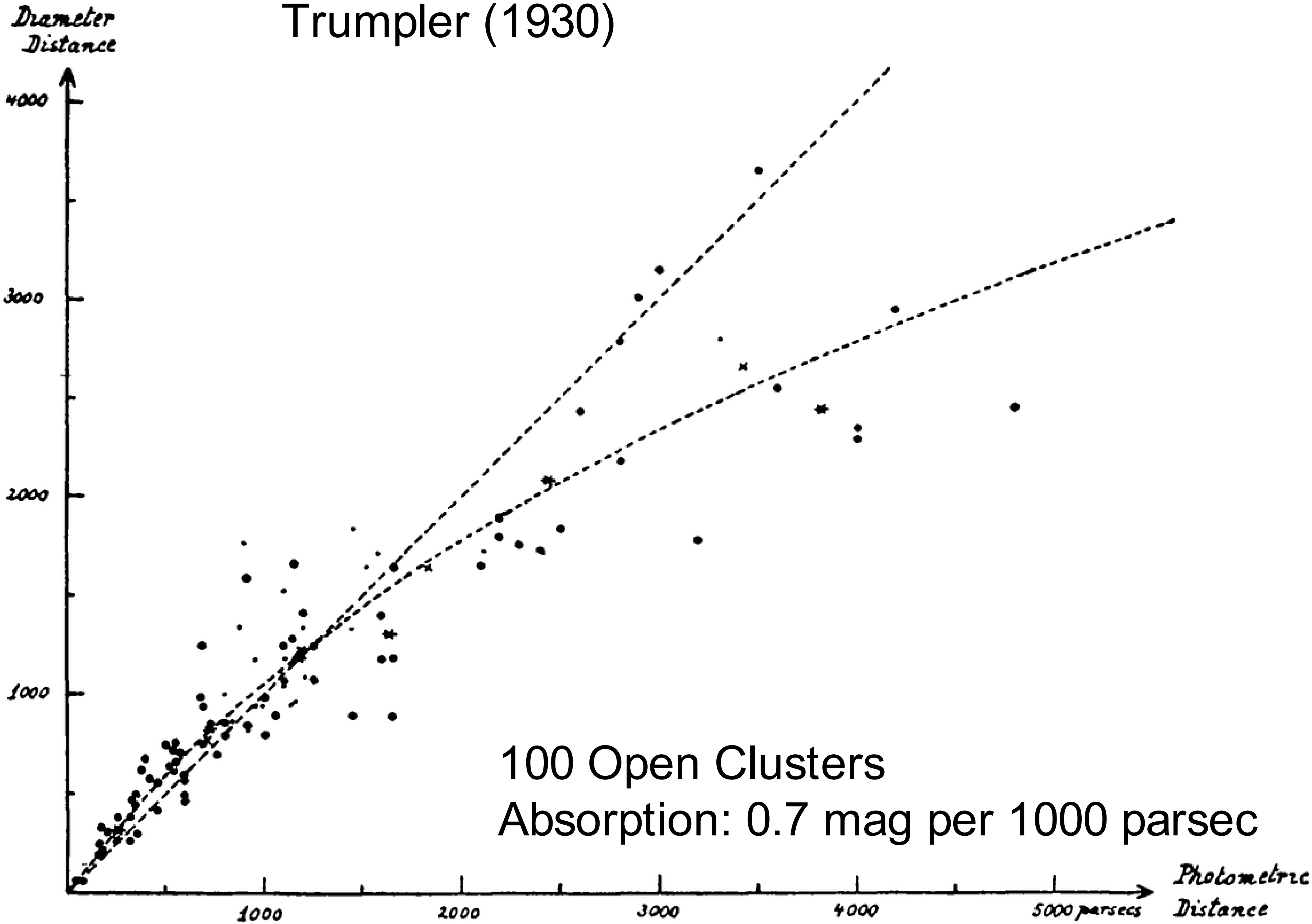
ESO PR Photo 20a/99 (30 April 1999)

IC 1396

CG 4

Thackeray's Globules

Trumpler (1930)



Extinction in the inner Galactic Bulge:
comparing infrared colors and magnitudes observed for AGB and RGB stars with those predicted from stellar evolution models

L72 M. Schultheis et al.: Interstellar extinction towards the inner Galactic Bulge

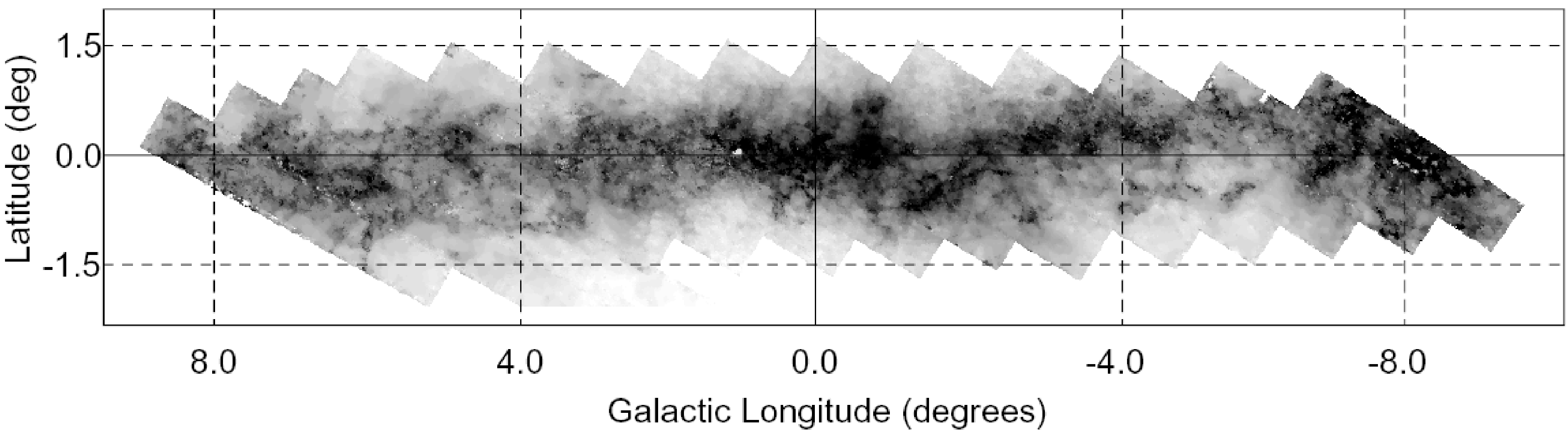
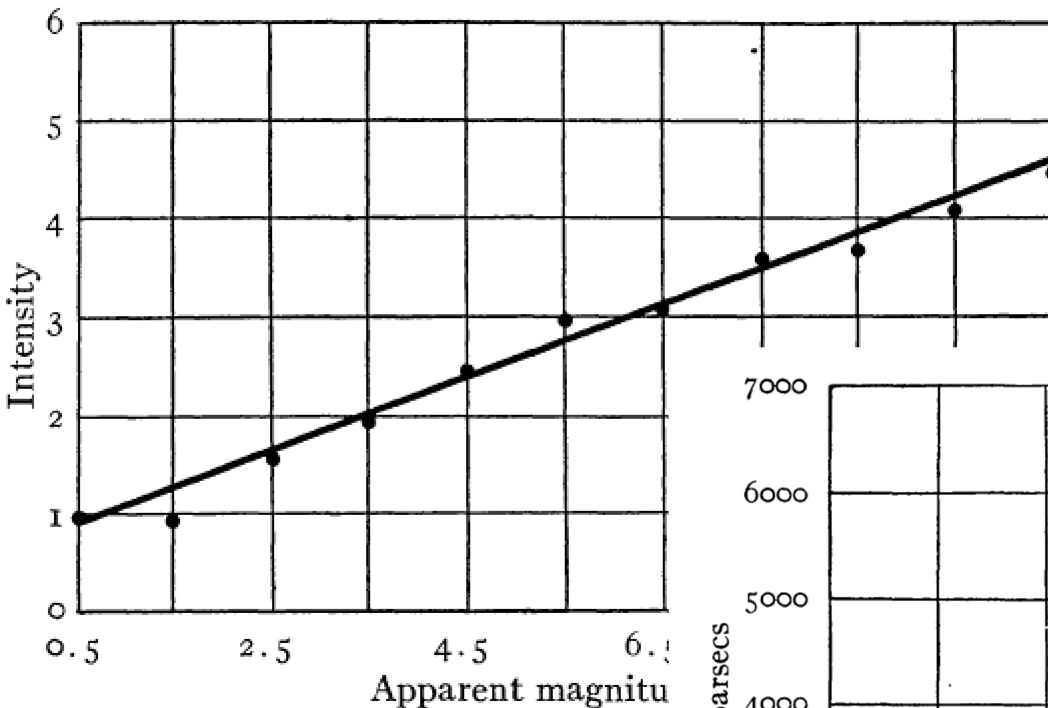


Fig. 3. Map of the extinction in the inner Galactic Bulge. The image grey scale represents an A_V range in magnitudes from 0 (white) to 35 (black). A coloured high resolution image can be found at http://www-denis.iap.fr/articles/extinction/

Struve (1928) Ca II K line in 1700 O-B3 stars



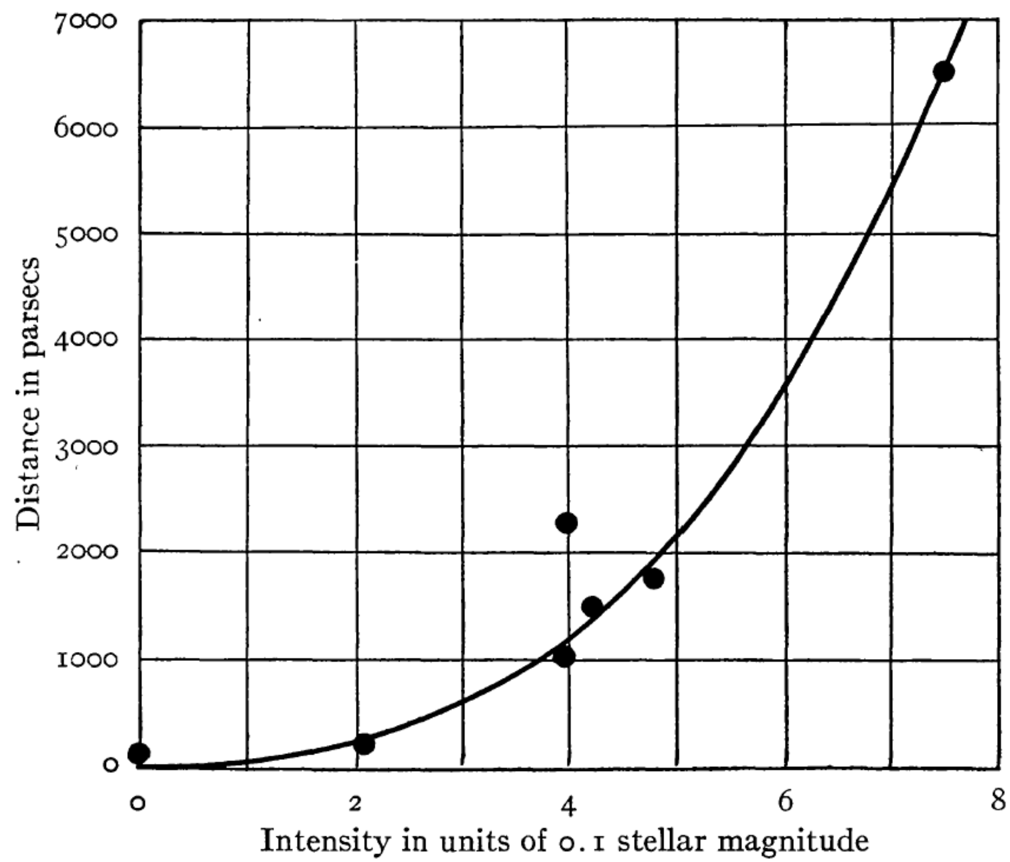


FIG. 6.—Relationship between intensity of detached K and distance

Red and blue light from nebulae

M 20

NGC 6559 and IC 1274-75

Interaction of stellar radiation with dusty gas clouds

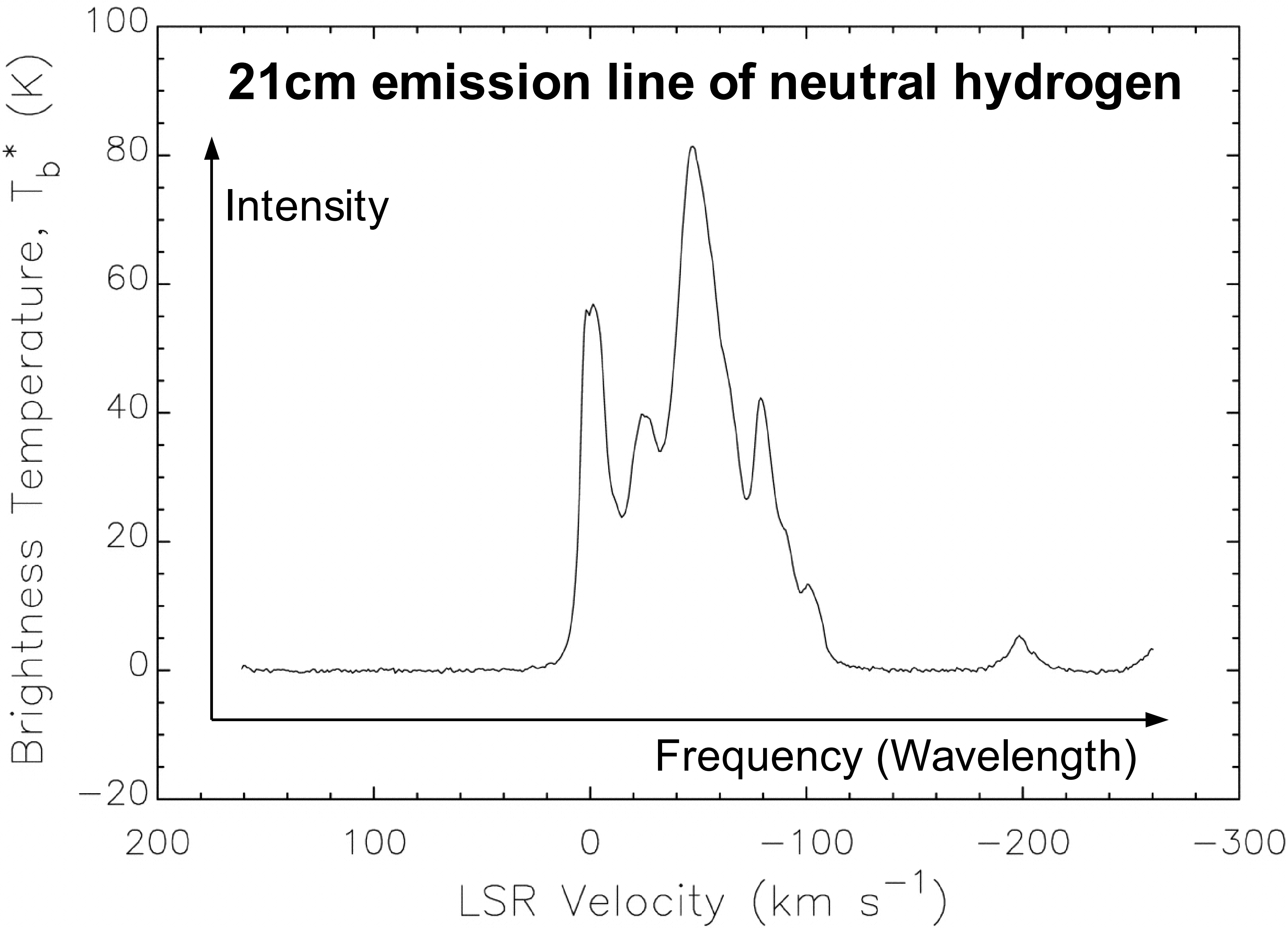
Horsehead Nebula

NGC 6188 and NGC 6193

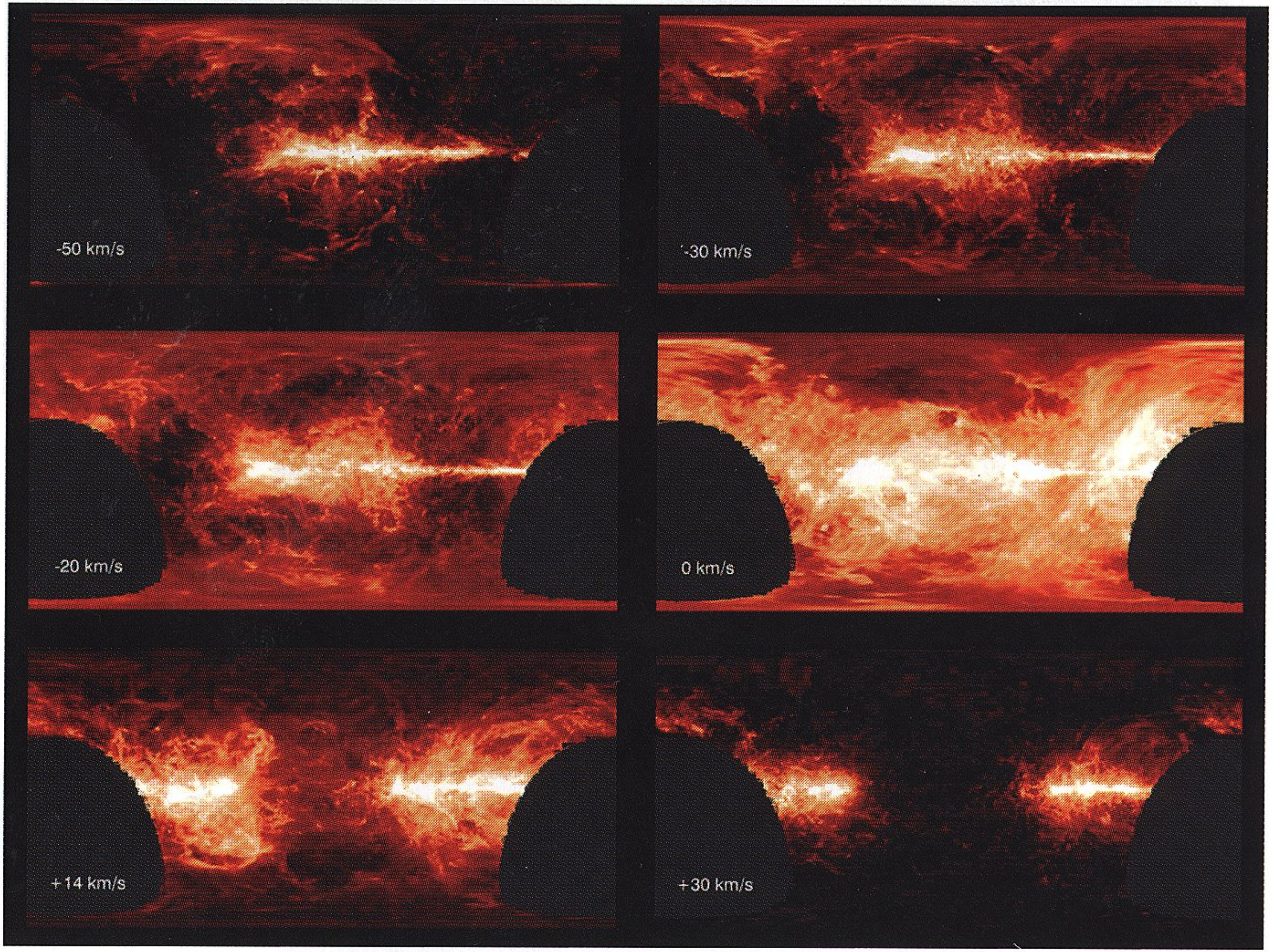
Dust in galaxies

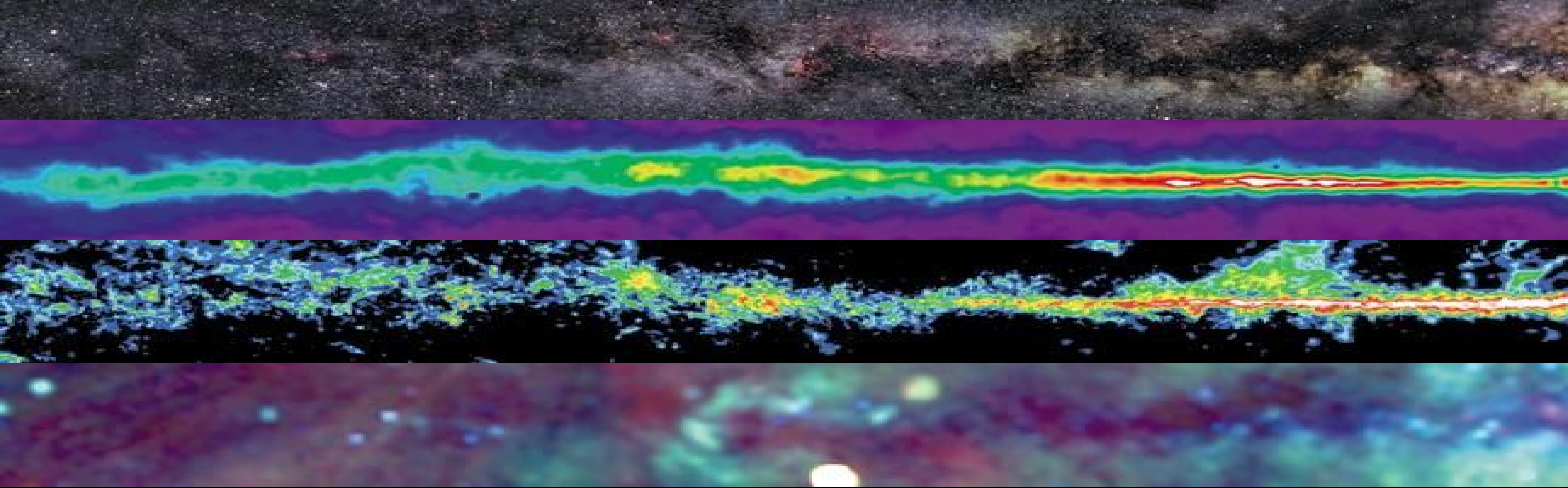
M 65

M 100

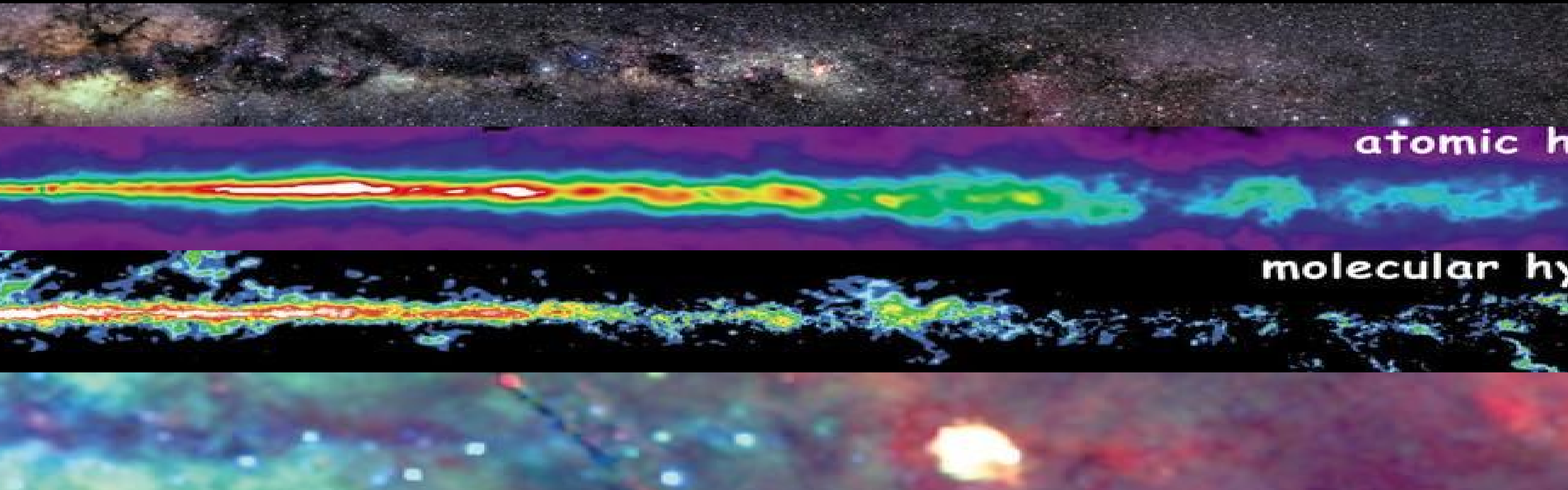


21cm emission line of neutral hydrogen
Intensity
Frequency (Wavelength)
Brightness Temperature, T_b^* (K)
100
80
60
40
20
0
−20
200
100
0
−100
−200
−300
LSR Velocity (km s^{-1})


-50 km/s
-30 km/s
-20 km/s
0 km/s
+14 km/s
+30 km/s



http://adc.gsfc.nasa.gov/mw/milkyway.html



Components of the ISM

- **Gas and dust:** several phases with different densities and temperatures
- **Radiation fields:** large local variations ionization, absorption
- **Velocity fields:** large scale flows as well as turbulent small scale motions
- **Magnetic fields**
- **Cosmic rays:** high energy particles

All have comparable energy densities:
~ 1eV/cm3

Structures within the Interstellar Medium

	Density [cm^{-3}]	Temperature [K]	Elements
Molecular clouds	> 100	10 – 20	H2, CO, ...
Diffuse clouds	10 – 1000	80	HI, other atoms, dust
Warm neutral medium	0.1 – 10	8000	HI, other atoms
Warm ionized medium	0.3 – 10	8000	HII, NII, SII, ...
Hot ionized medium	< 0.01	5×10^5	HII, OVI, NV, SiIV
HII regions	$10 - 10^4$	8000	HII, OII, OIII, ...
Ultracompact HII regions	$10^4 - 3 \times 10^5$	8000	HII
Planetary nebulae	$100 – 10^4$	10^4	HeII, OII, NeIV, ...
Supernova remnants	> 1	$10^4 - 10^7$	HII, HeII, OII, OIII, SII, ...

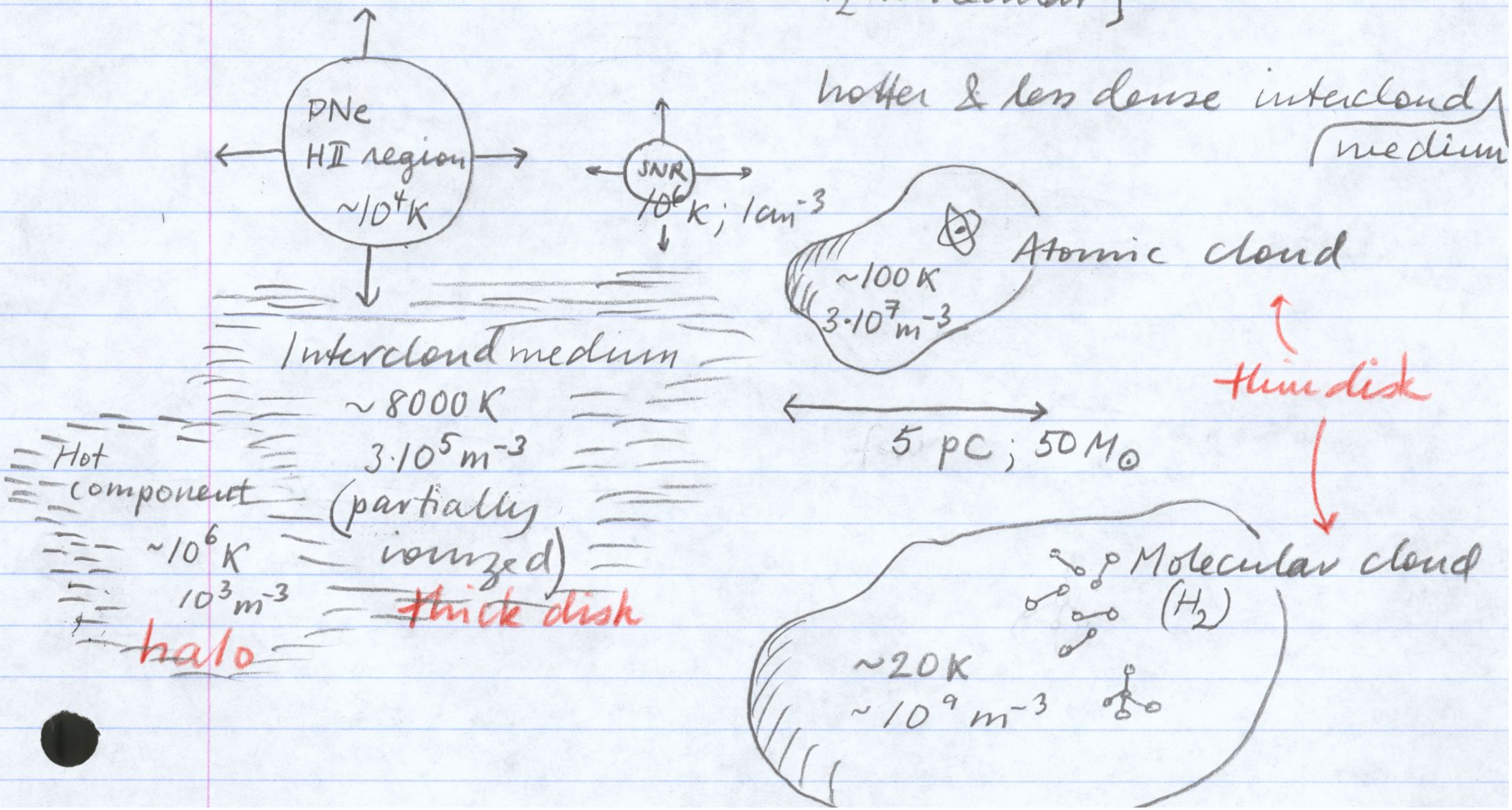
from Allen´s Astrophysical Quantities, p. 524

Structures within the Interstellar Medium

	Mass [M_sun]	Height [pc]	Observations
Molecular clouds	10^9?	40 – 60	radio, near-IR, near-UV
Diffuse clouds	1.5×10^9	100	radio, IR, optical
Warm neutral medium	1.5×10^9	500	radio, optical
Warm ionized medium	10^9	1000	optical, UV
Hot ionized medium	10^8	3000	X-ray
HII regions	5×10^7		optical, IR
Ultracompact HII regions			radio
Planetary nebulae			optical
Supernova remnants			radio, IR, optical, X-ray

Cartoon 2 General picture of ISM

$\left.\begin{array}{l} H\text{-atomic} \\ H_2\text{-molecular} \end{array}\right\}$ clouds



← 20 pc →

Characterstic densities

Dust: ~ 1-10% of gas mass

grain size: 0.1 - 0.001 mm,

~ 1 grain/10^6 m^3

~ 0.001 M_{sun}/pc^3

Gas: ~ 10^6 atoms/m^3

~ 0.01 M_{sun}/pc^3

H: 90%, He: 10%, CNO: 0.1%

gas atoms/dust grains by number = 10^{12}

Interstellar lines

Often many components towards distant stars in the galactic plane.

- Na I D lines 589, 589.6 nm
- Ca I 422.7 nm
- Ca II H and K lines, 393.4, 396.8 nm
- 21 cm HI hfs line of $^2S_{1/2}$ ground state.
- Recombination lines

Ionized regions show recombination spectra
e.g. H I n = 109 $\rightarrow$ n = 108 line at 5009 MHz
etc. to Hα and Lyα

Some important molecular lines

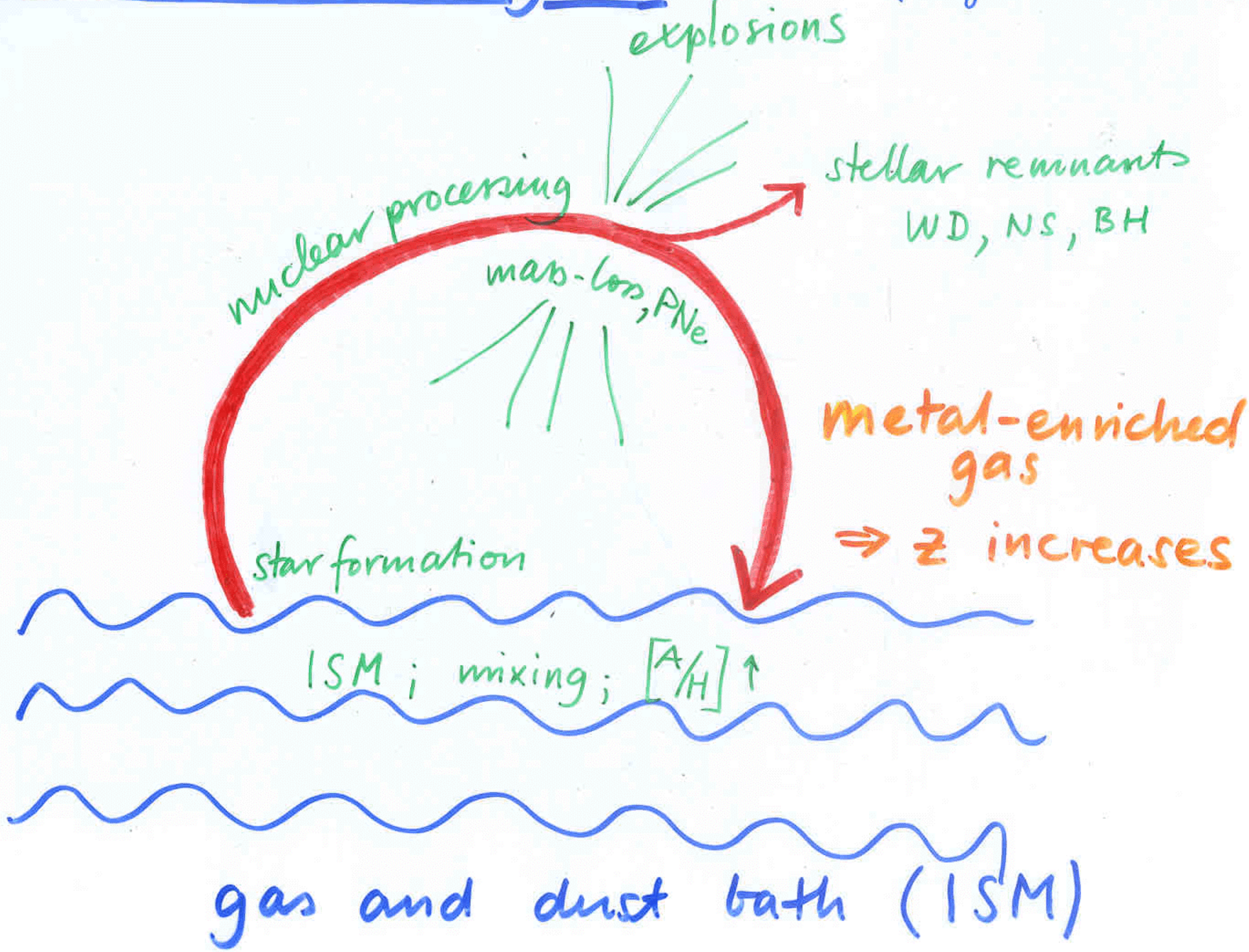
- **OH 18 cm, 4 lines**
- **SiO 3, 45 mm**
- **SO 3.02 mm, …**
- **CO 2.6, 1.3, 0.87 mm**
- **CN 2.6 mm**
- **CH 9.2 cm**
- **CS 6.1, 3.1, 2.0 mm**
- **H_2O 13.5, 1.63 mm**
- **H_2S 1.78 mm**
- **NH_2^+ 3.22 mm**
- **C_2H 3.4 mm, 2 lines**
- **NH_3 12.6 mm, 2 lines**
- **HCN 3.38 mm**
- **HNC 3.31 mm**
- **HCO^+ 3.37 mm**
- **H_2CO 6.21, 2.07 cm**
- **CH_3OH 3.1 mm, 3 lines**

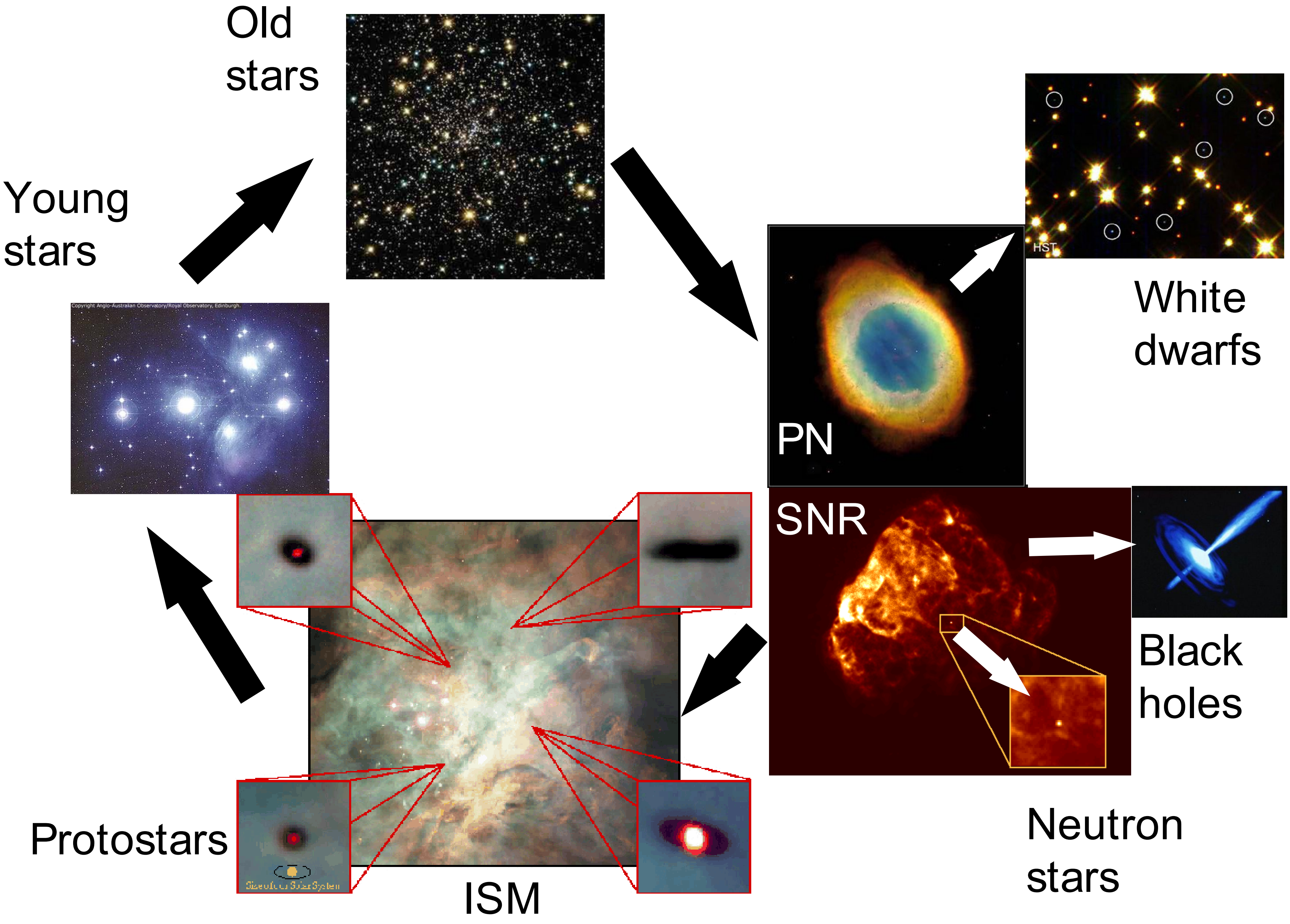
The Cosmic Cycle

(Hoyle et al '50ies)

Important:

- $\dot{M}$
- timescales





Old stars
Young stars
Copyright Anglo-Australian Observatory/Royal Observatory, Edinburgh.
HST
White dwarfs
PN
SNR
Black holes
Neutron stars
Protostars
ISM

Life cycle of stars

NGC 3603 **HST • WFPC2**

PRC99-20 • STScI OPO • June 1, 1999

Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (Univ. Washington), You-Hua Chu (Univ. Illinois, Urbana-Champaign) and NASA

Intimate relation between gas, dust, and young stars.

M 16

M 8

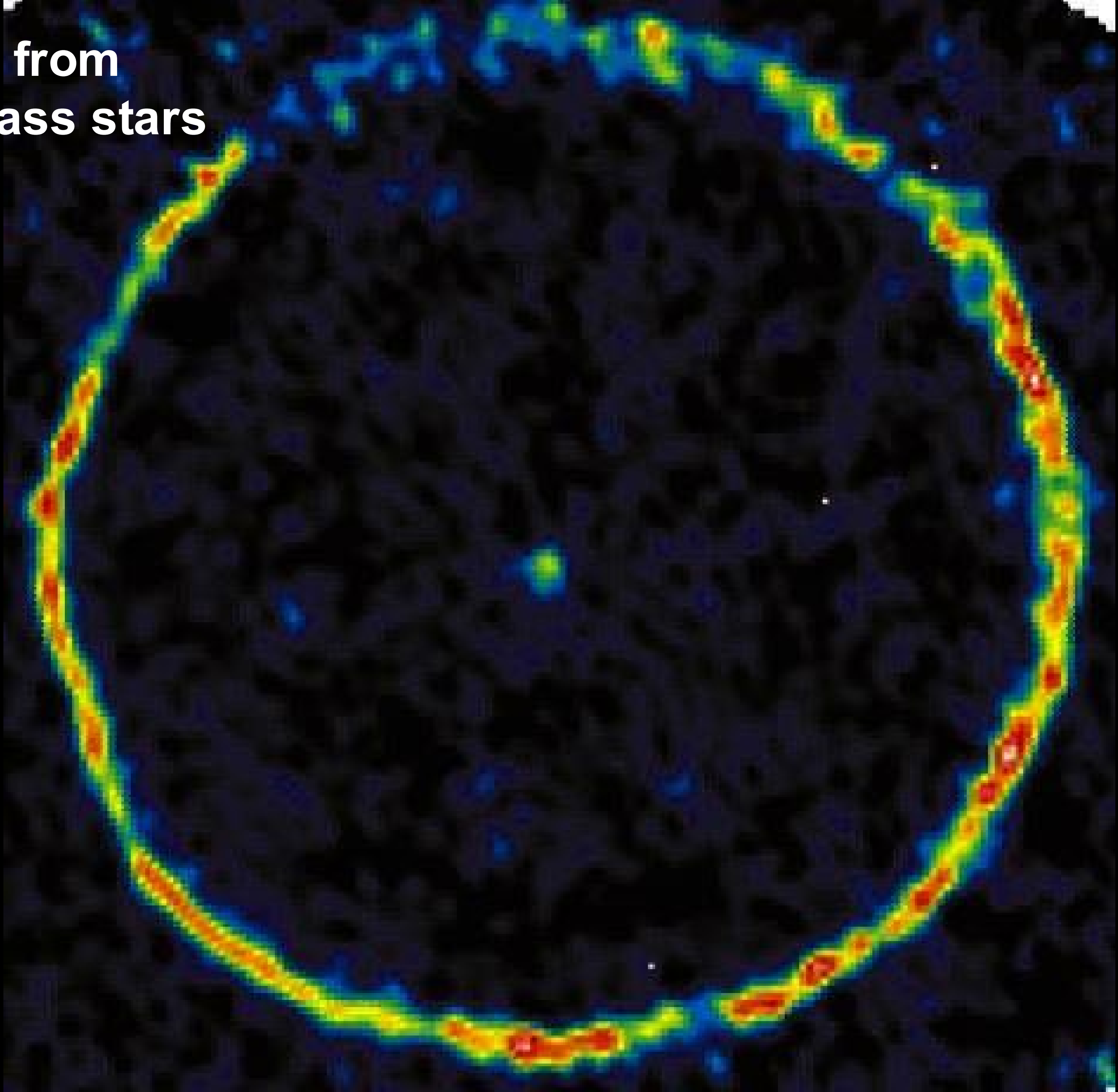
M 17

Winds from high-mass stars

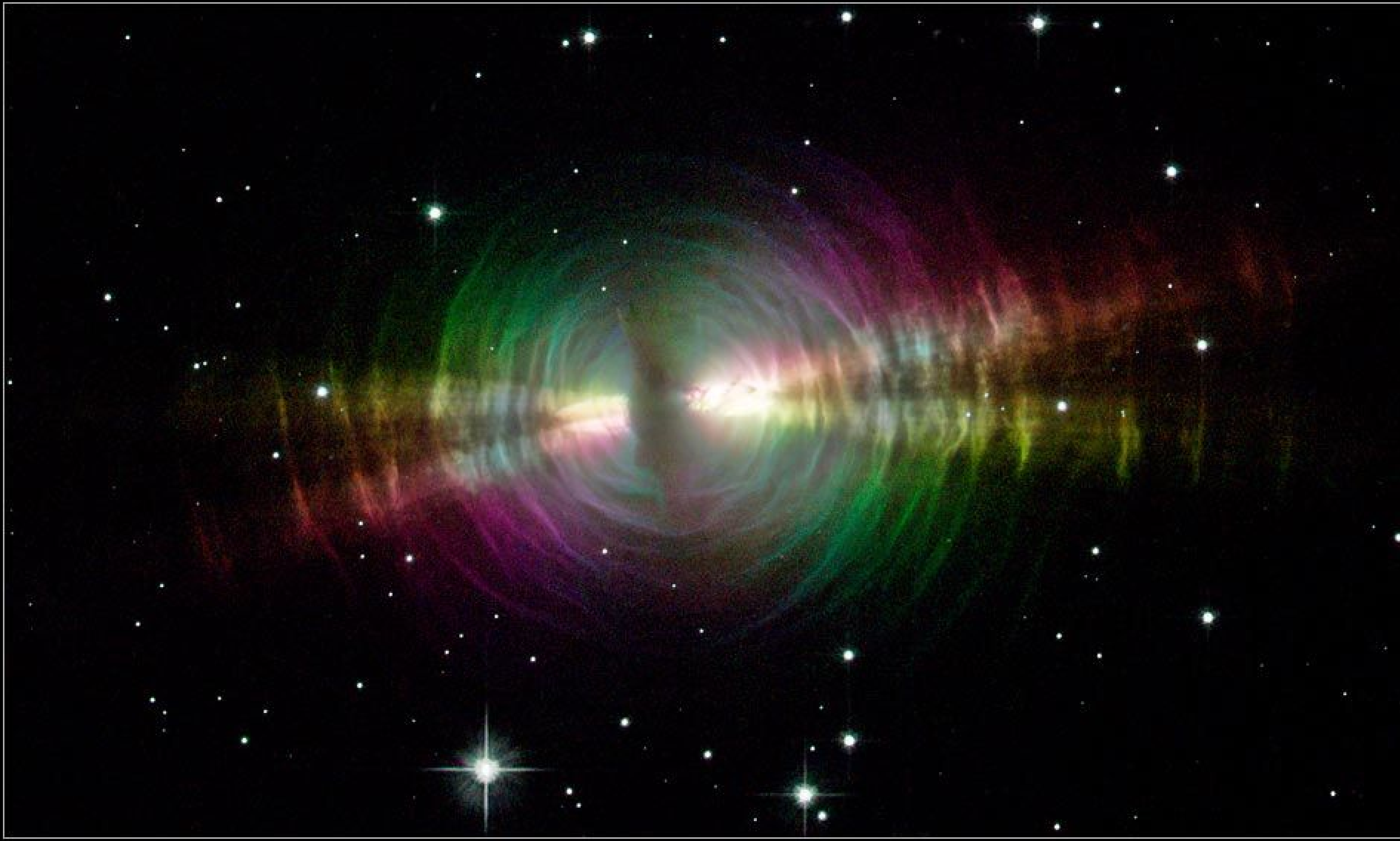
Wolf-Rayet star

Henize 70 (LMC)

Winds from low-mass stars

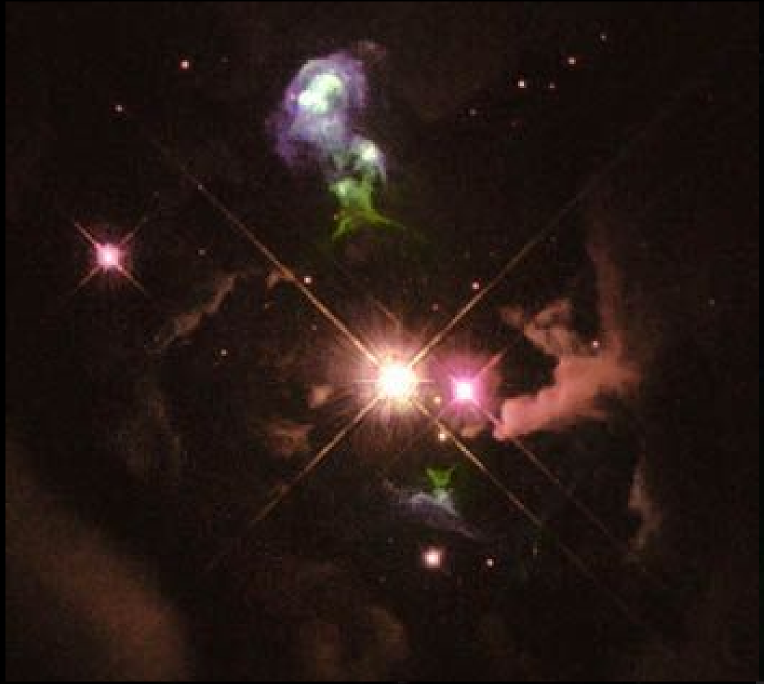


The Egg Nebula



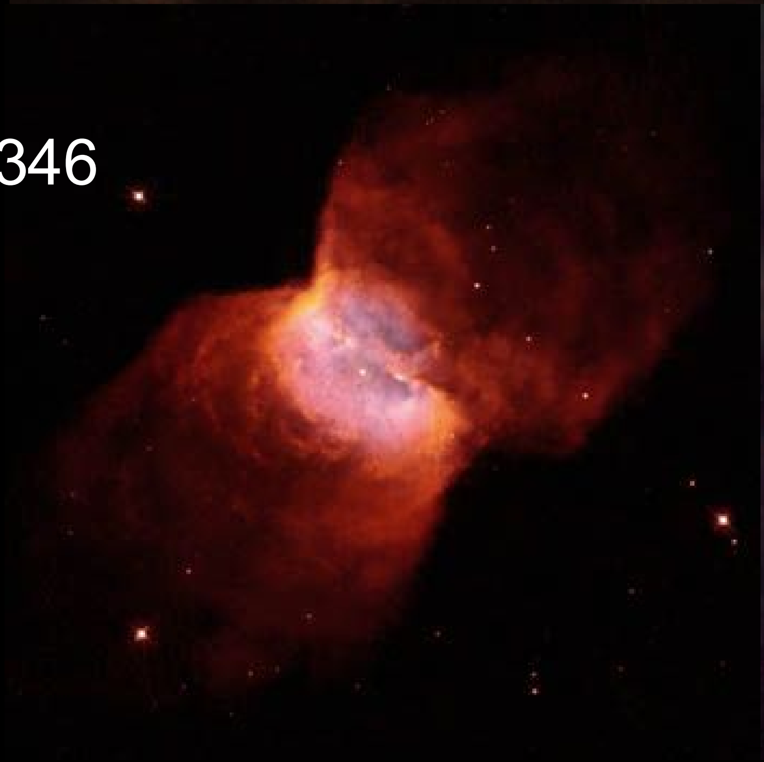
Hubble Heritage

HH 32



Hubble's variable nebula

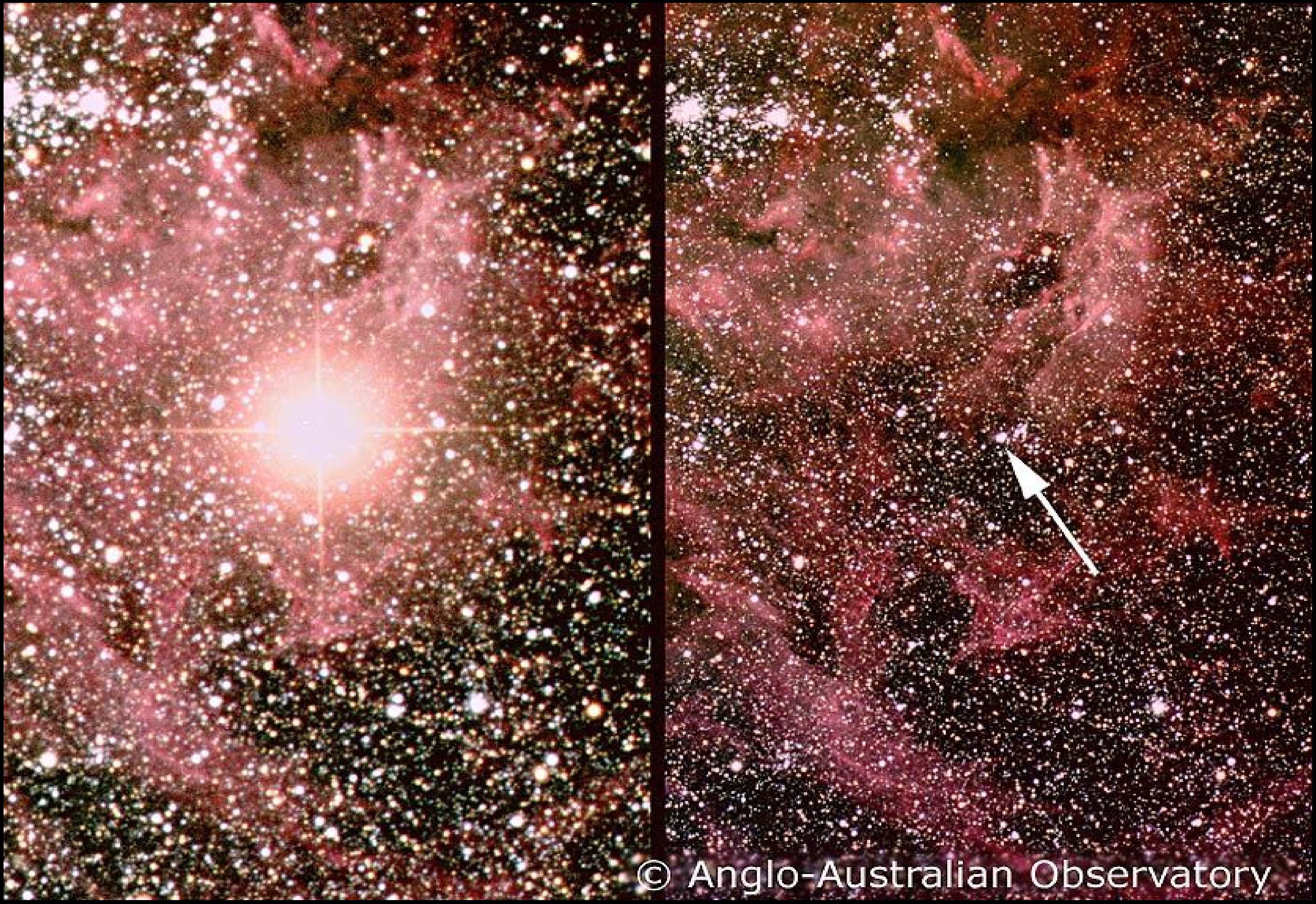
NGC 2346

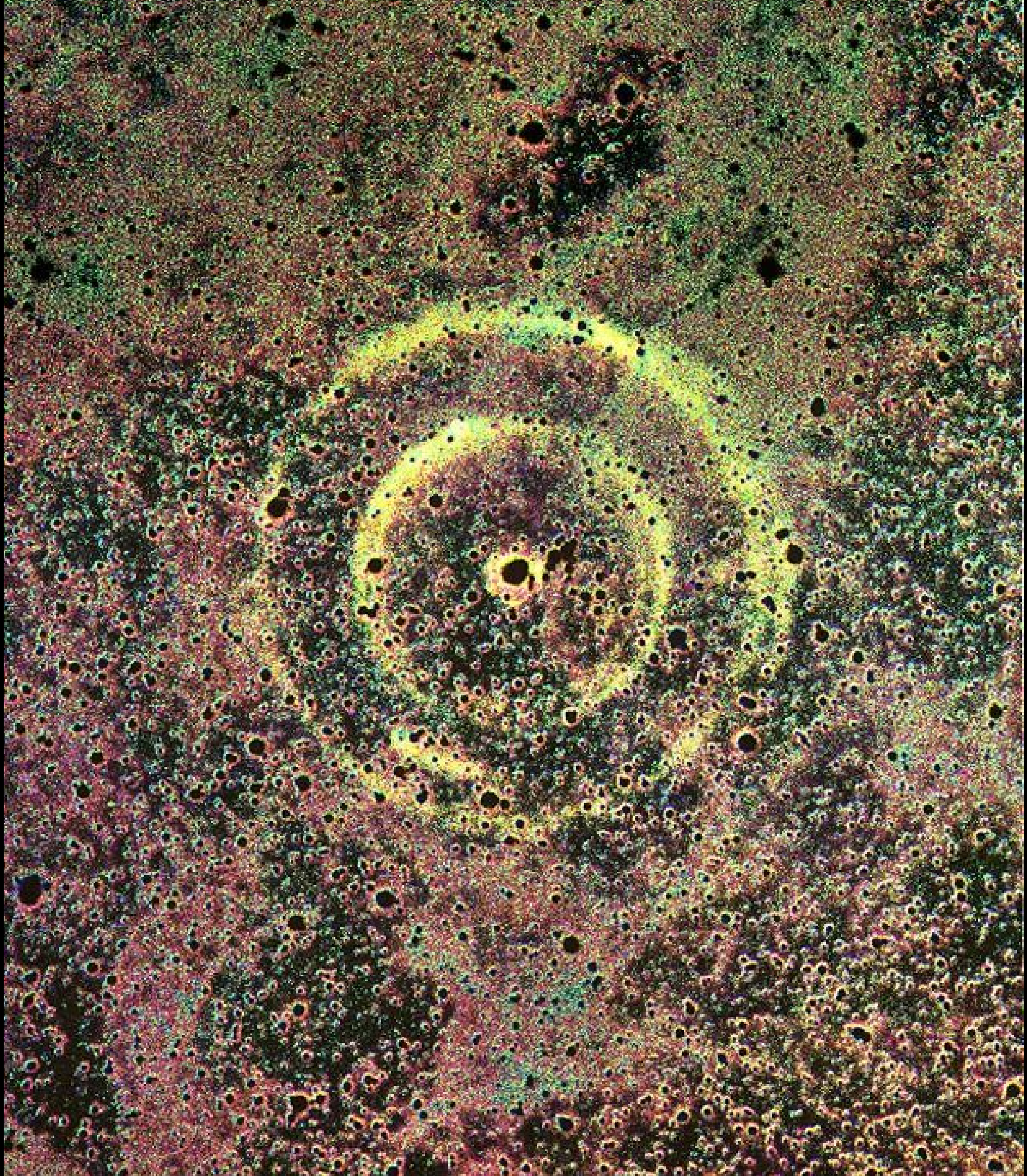


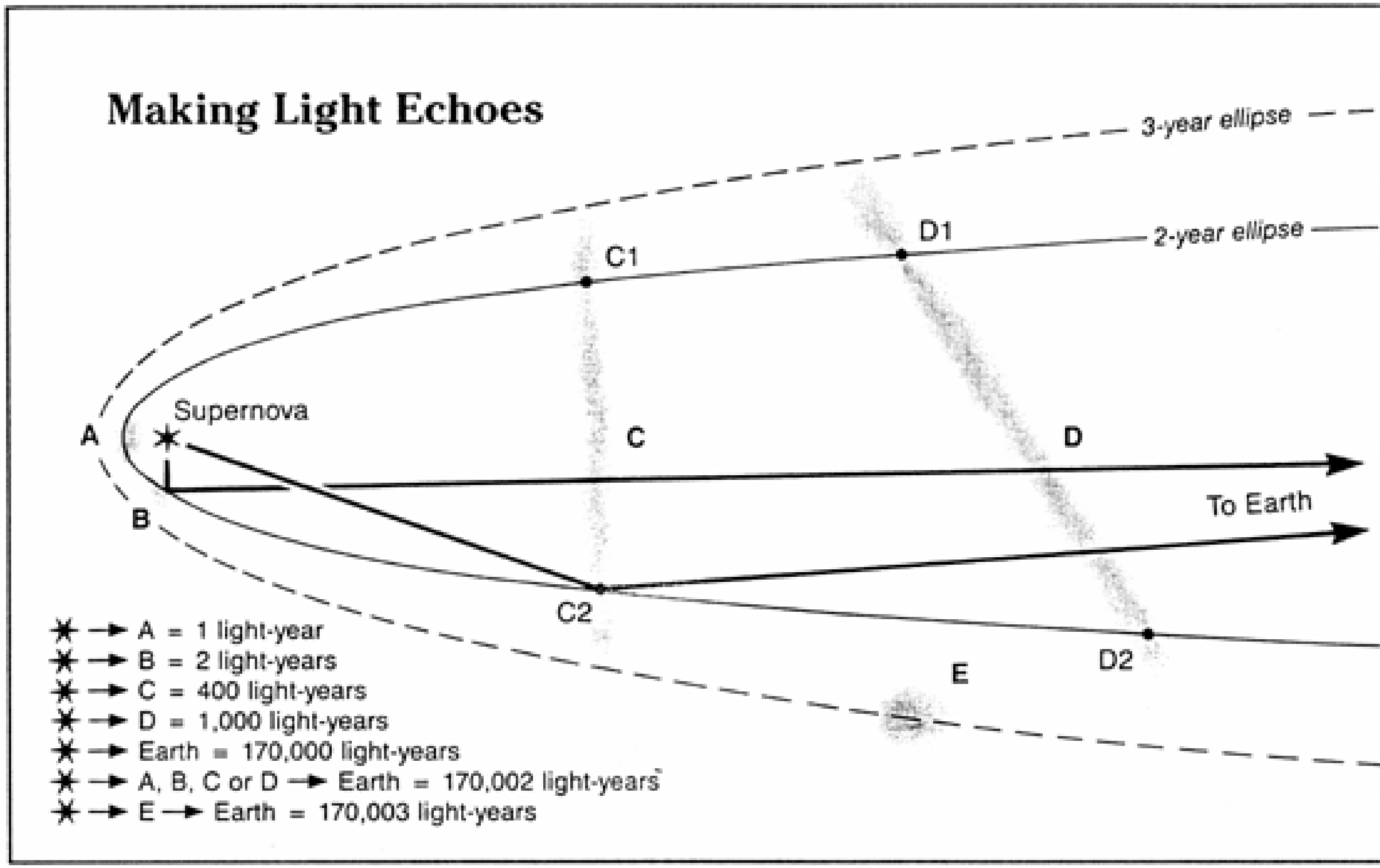
NGC 2440

Planetary nebulae

Supernovae





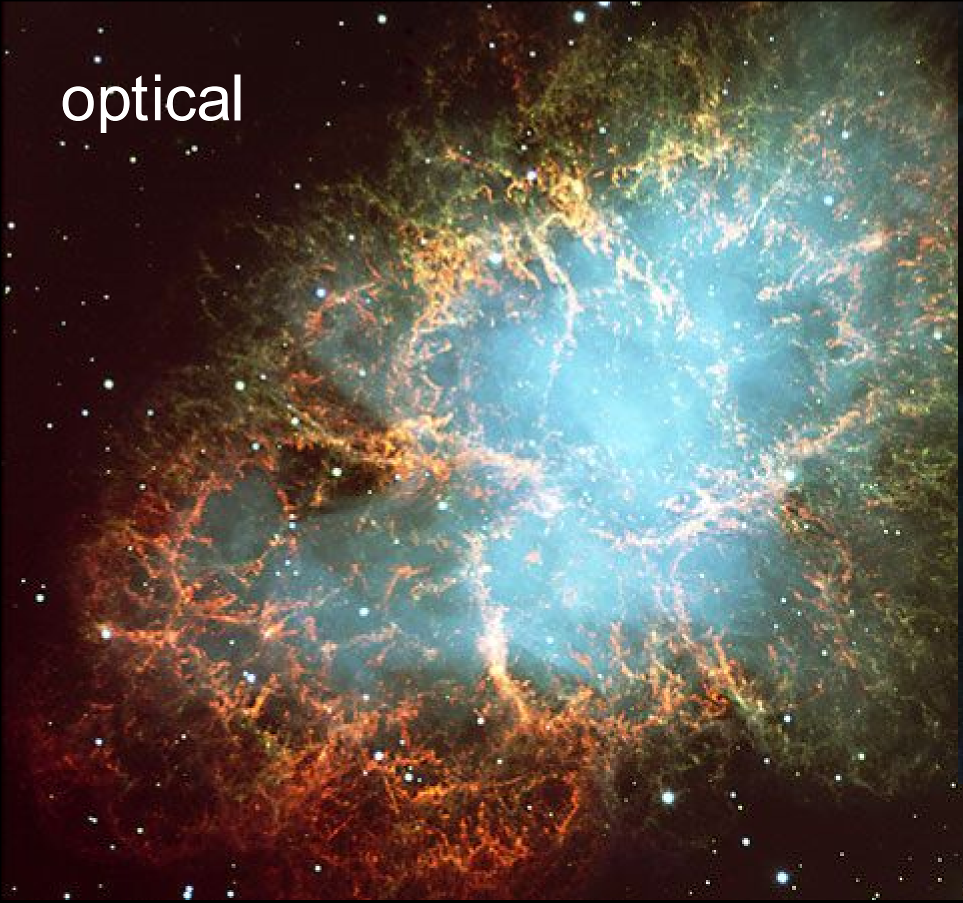


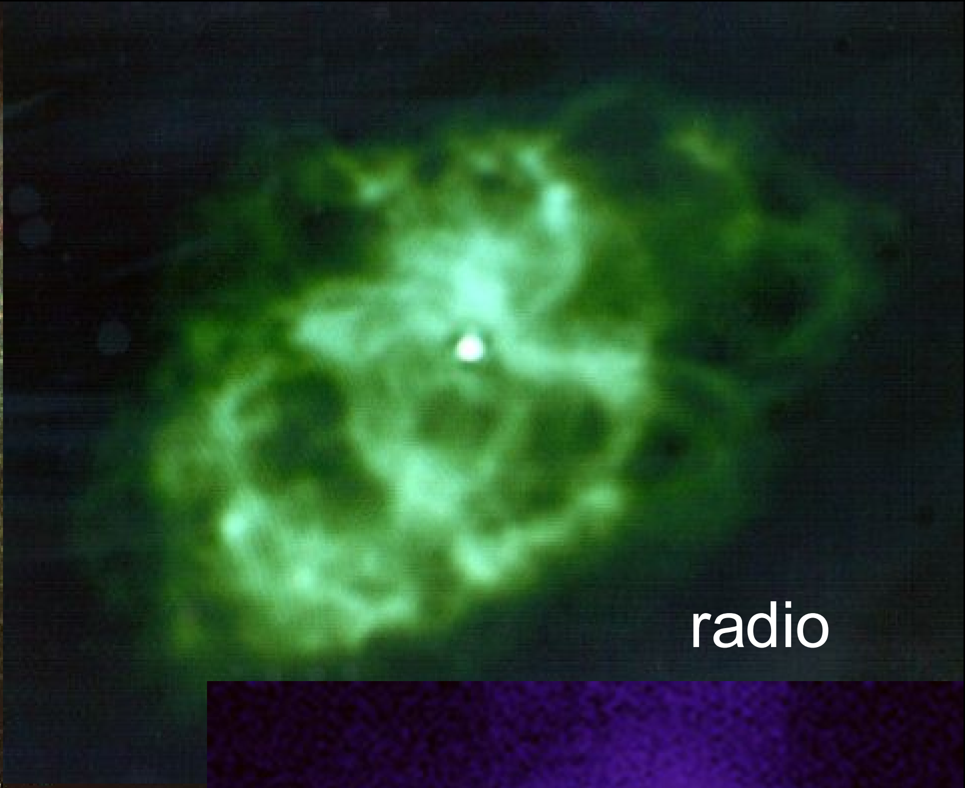
How light echoes are formed. The gray areas are clouds of dust. As discussed more fully on page 25, echoes can come not only from material behind the supernova (*A*), but also from dust at the same distance (*B*) and even closer to us than the explosion (*C*, *D*, and *E*). Wherever these interstellar clouds intersect the inner, solid ellipse we will see a light echo two years after the supernova's maximum light. After three years the echo ellipse has expanded to the dashed line and the echoes have moved outwards, revealing dust cloud *E*. For clarity the clouds of reflective particles have been drawn much closer to the supernova than they are in reality, and the ellipses and relative location of the supernova are not to scale. The ellipses are actually extremely narrow.

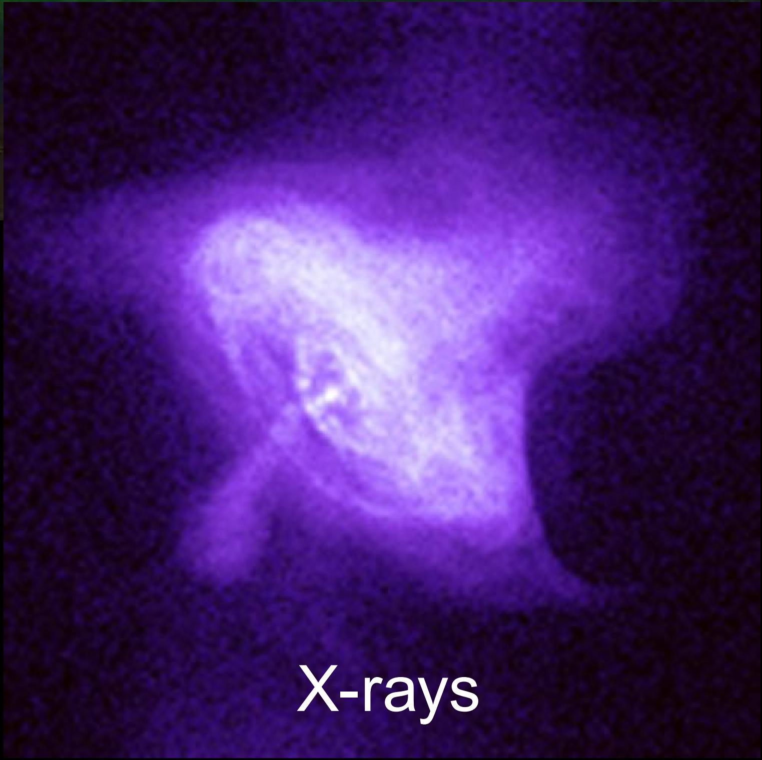
Supernova remnants

Pencil Nebula

Vela SNR

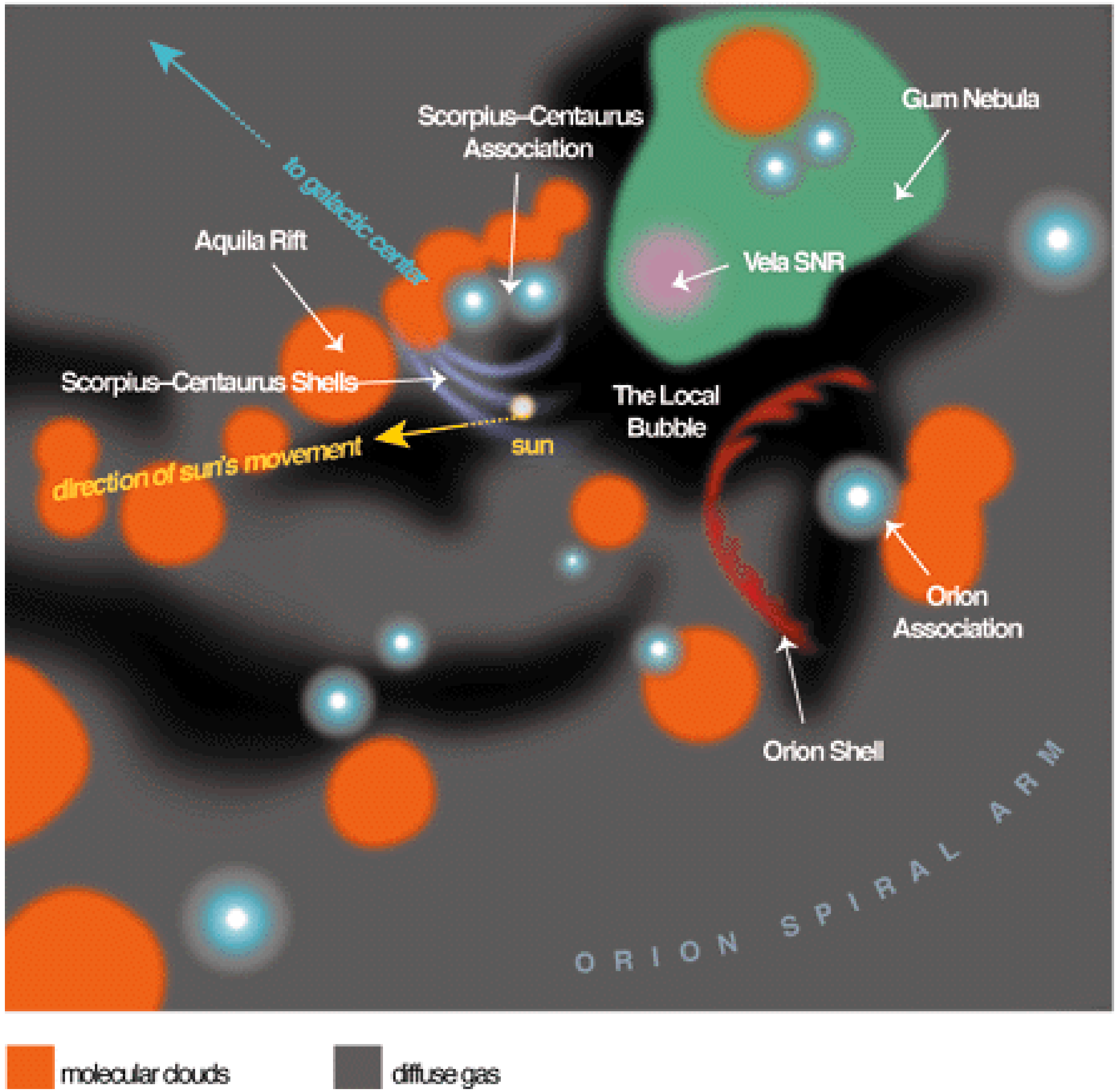






Crab Nebula

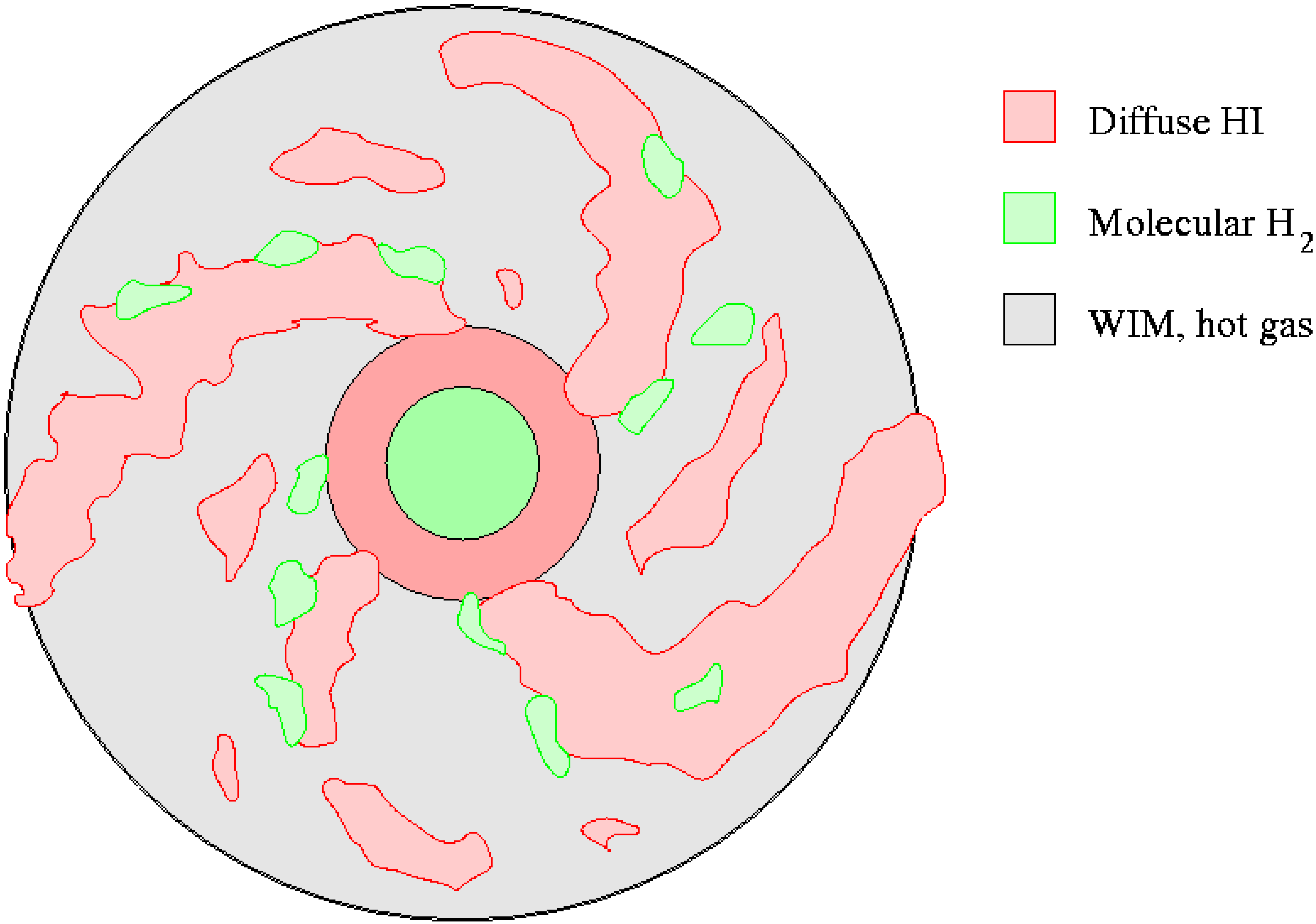
Local ISM (1500 light years)



see also talk by Jeff Linsky:

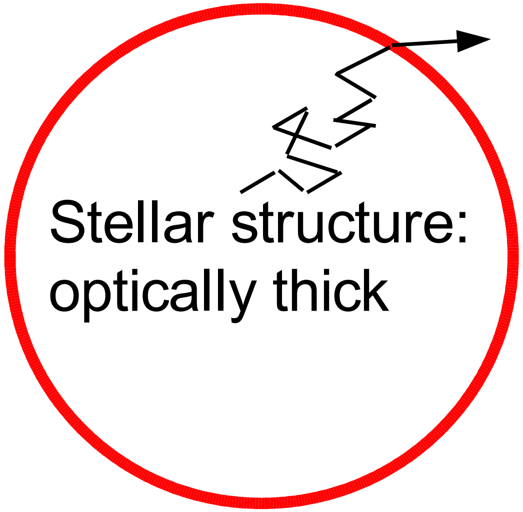
http://www.astro.uu.se/forskarutb/LISM/LISM.html

Milky Way disk from above



EM radiation - Spectroscopy

Star



Stellar atmosphere:
optical depth around 1

Sun:
rho = $10^{-7} – 10^{-10}$ g/cm^{-3}
P_{gas} = nkT = $10 – 10^4$ N/m^2
4000 < T < 10000 K
=> n = $10^{17} – 10^{14}$ cm^{-3}

ISM:
optically thin
low density
low particle density
low pressure

- winds
- explosions
- star formation

We need:

1. **Radiative transfer**
2. **Atomic and molecular physics (micro-physics): cooling and heating**
3. **Gas physics and dynamics (macro-physics): motions of ISM gases, shock fronts, IF, stellar winds, and explosions**