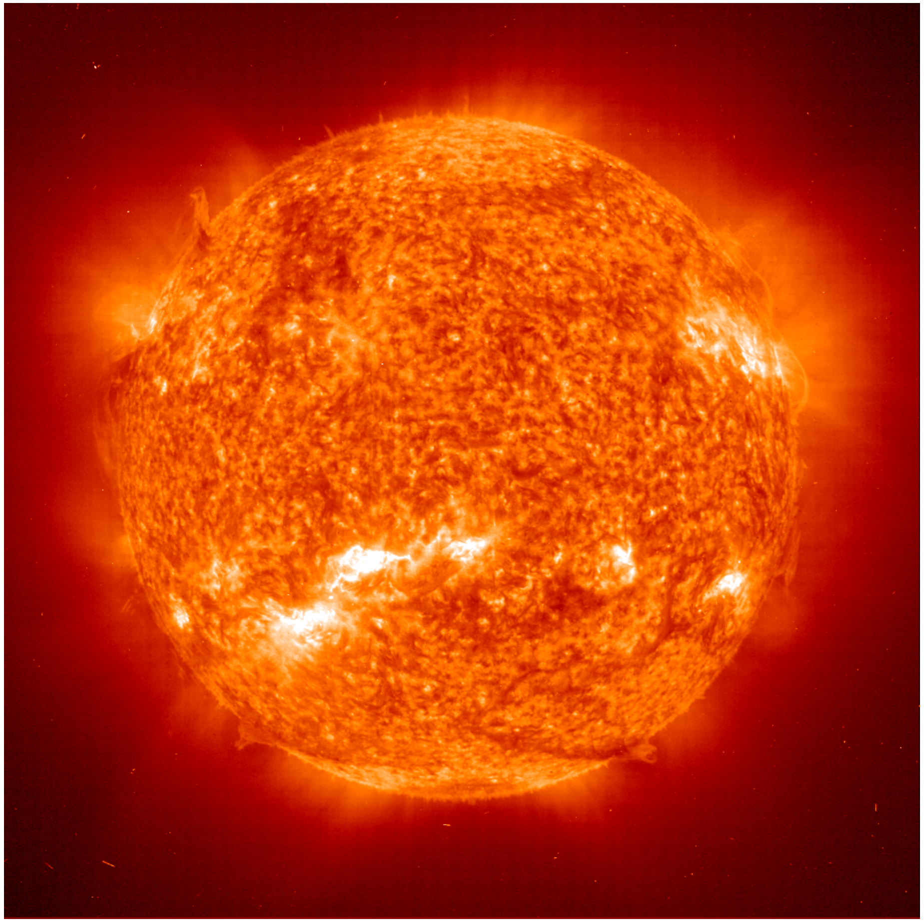
Structure and Evolution of Stars

Paul Hewett, Michaelmas 2017



SOHO image of the Sun in far-UV light

Structure and Evolution of Stars

Lecture 1: Overview

- Schedules
- Textbooks
- Pictorial run through of course
- Stellar metallicities and stellar populations
- Stars and galaxies

STRUCTURE AND EVOLUTION OF STARS
Michaelmas Term 2017: 24 Lectures

Schedules

1) Basic Concepts and Observational Properties

- Course overview
- Mass, Temperature, Luminosity Gravity, composition, Age
- Photometry and stellar colours; Spectra and spectral lines
- Distance: parallax, apparent and absolute magnitudes
- Masses from binary stars
- Temperature: black-body radiation, Wien's Law
- The Hertzsprung-Russell Diagram and spectral classification

2) Stellar Structure

- Timescales; dynamical, thermal nuclear
- Energy generation, thermonuclear reactions
- Energy transport; opacity, radiative and convective transport
- Equations of stellar structure

STRUCTURE AND EVOLUTION OF STARS
Michaelmas Term 2017: 24 Lectures

Schedules

2) Stellar Structure (cont.)

- Hydrostatic equilibrium, Virial Theorem, Pressure
- Stellar properties as a function of mass, homology
- Degeneracy: Chandrasekar limit

3) Stellar Evolution and the Hertzsprung-Russell diagram

- Pre-main sequence evolution, Hayashi and Henyey tracks
- Post-main sequence evolution: massive stars, supernovae, neutron stars, black holes
- Post-main sequence evolution: low-mass stars, planetary nebulae, white dwarfs, Type Ia supernovae
- Initial mass function

Schedules (continued)

4) Observational Tests and Constraints

- The mass-luminosity relationship
- Stellar abundances
- The most massive stars and stellar winds
- Supernovae

Recommended Text Books

- Prialnik, D., An Introduction to the Theory of Stellar Structure and Evolution, Cambridge University Press, 2000, 2nd Edition 2010
  - Best overall match to course
- Phillips, A.C., The Physics of Stars, Wiley, 2nd Edition, 1999
  - Quite excellent on the physics of the course
- Green, S. & Jones, M., An Introduction to the Sun and Stars, Cambridge University Press, 2004
  - Gentle modern introduction to the observational aspects of the course. Very good figures

Recommended Text Books

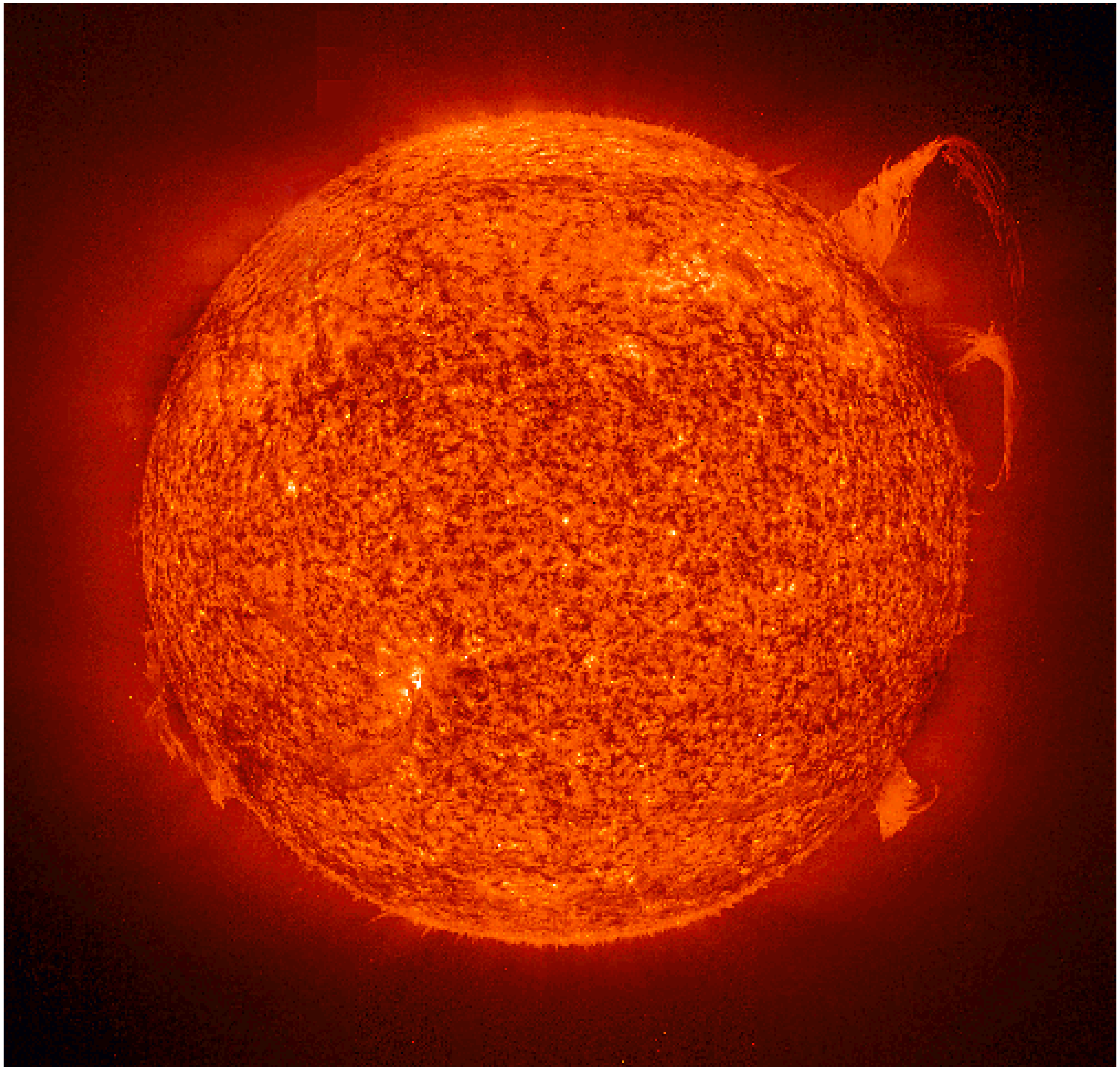
- Ostlie, D.A. & Carroll, B.W., An Introduction to Modern Stellar Astrophysics, Addison-Wesley, 1996, 2nd Edition 2013
  - North American and fairly voluminous but some very good parts

- Tayler, R.J., The Stars: Their Structure and Evolution, Cambridge University Press, 1994
  - Low-level overview but quite sound

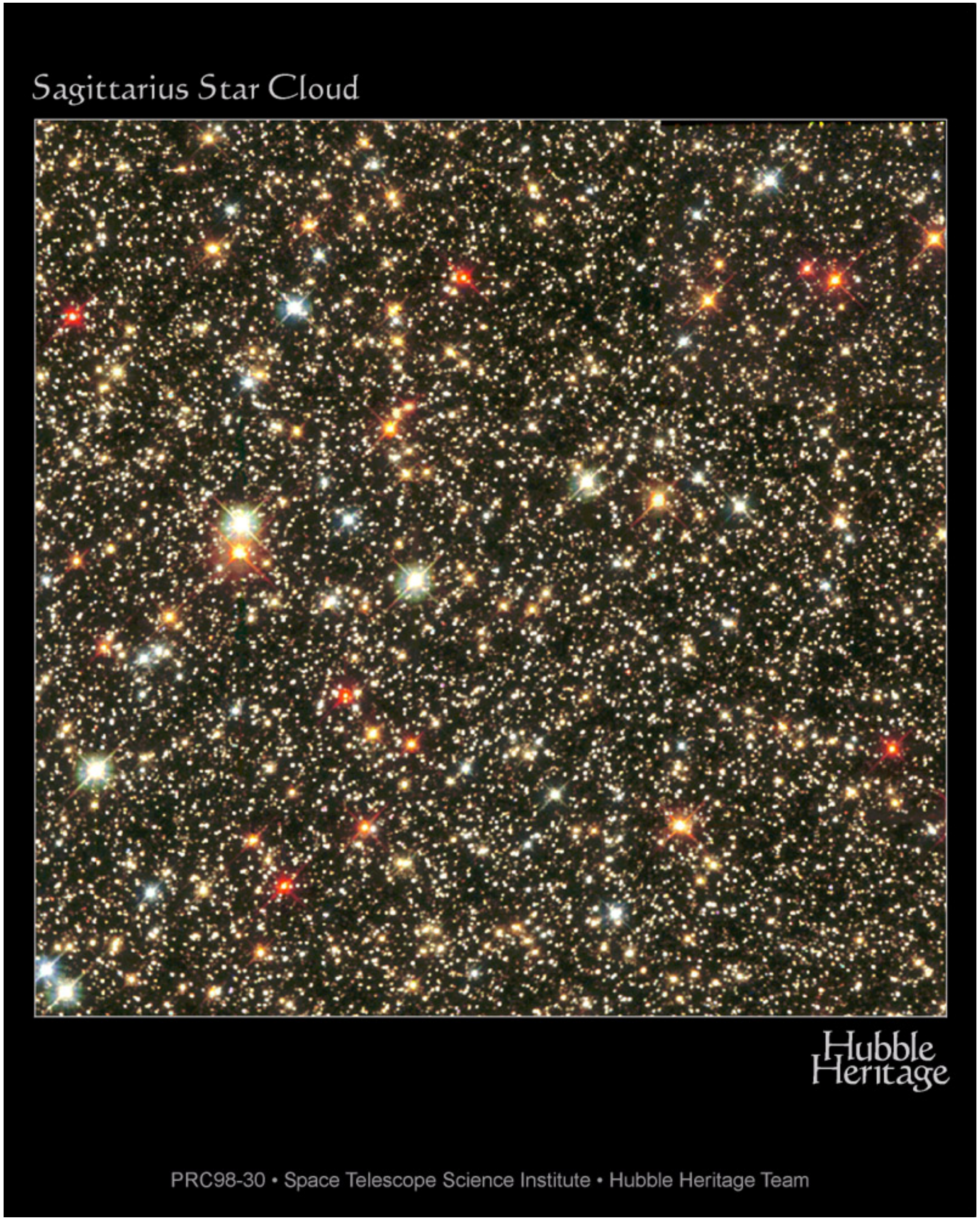
- Lecture notes on line at: http://www.ast.cam.ac.uk/~phewett/SandES2017/

Sun

Mass = 2×10^{30}kg
Radius = 7×10^{8}m
Lum = 3.9×10^{26}W
Temp = 5800K



SOHO image at 304A

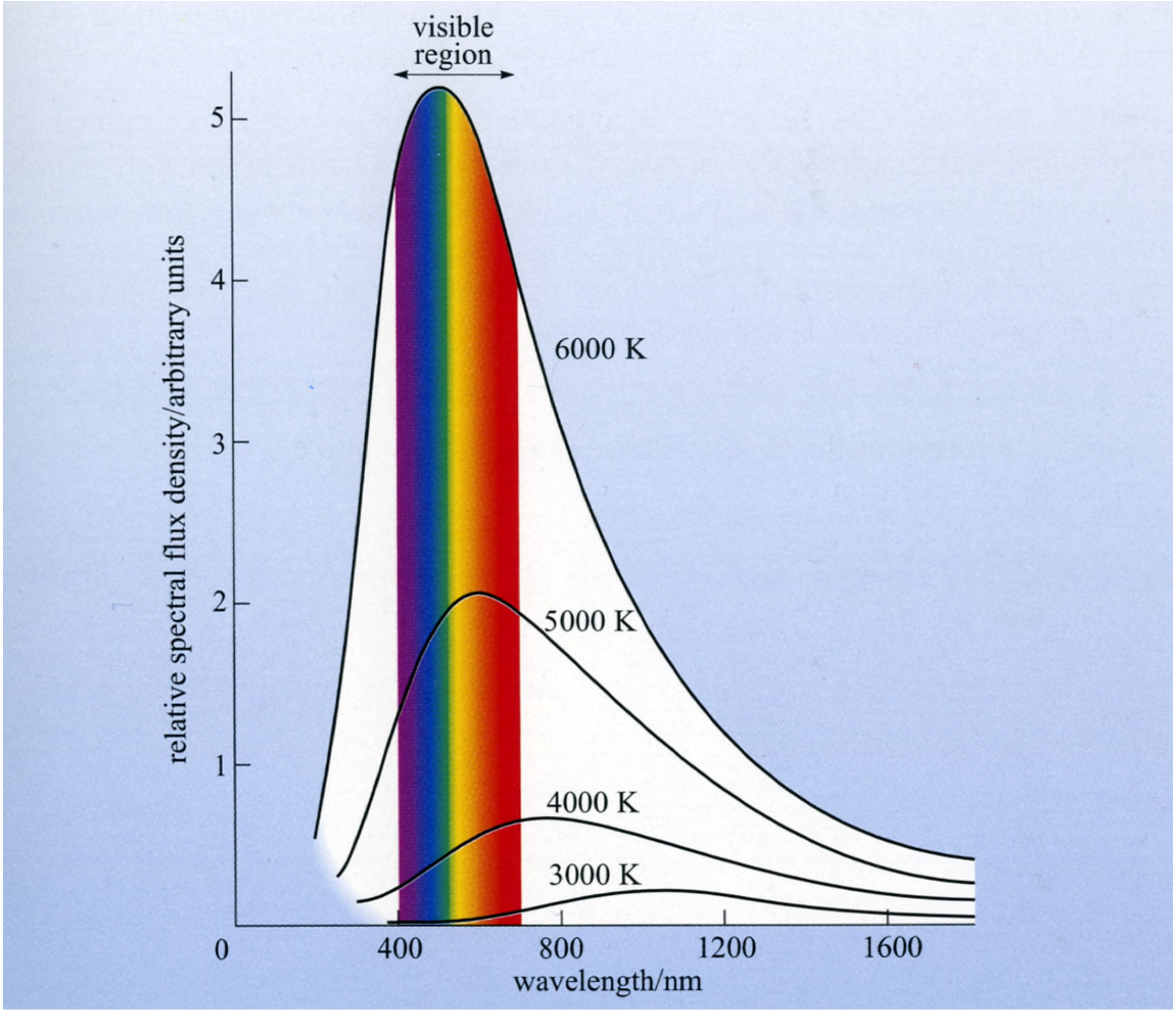


HST image of star field towards centre of the Galaxy

Luminosity?
Mass?
Radius?
Temperature?

Distance is essential

Blackbody curves for different T



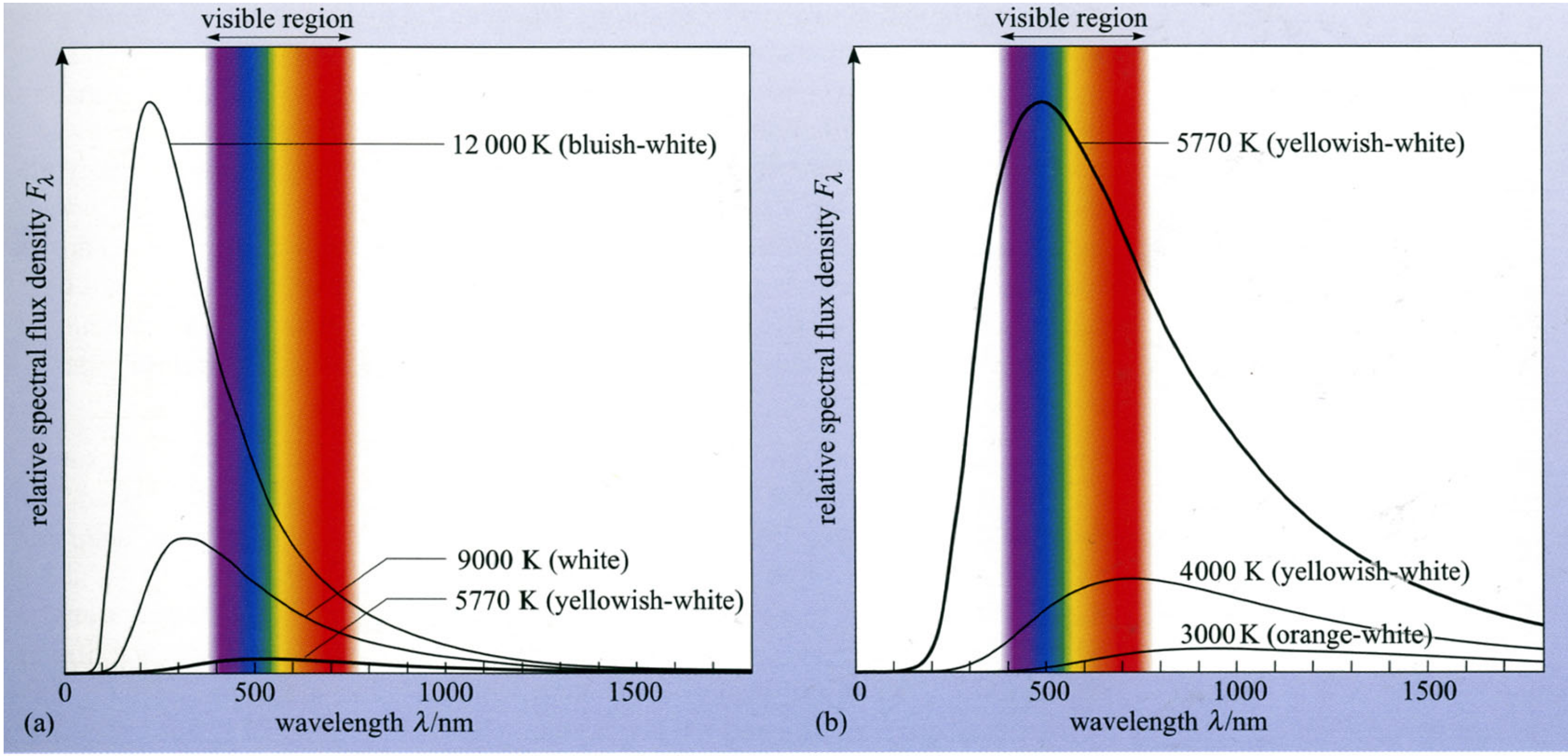
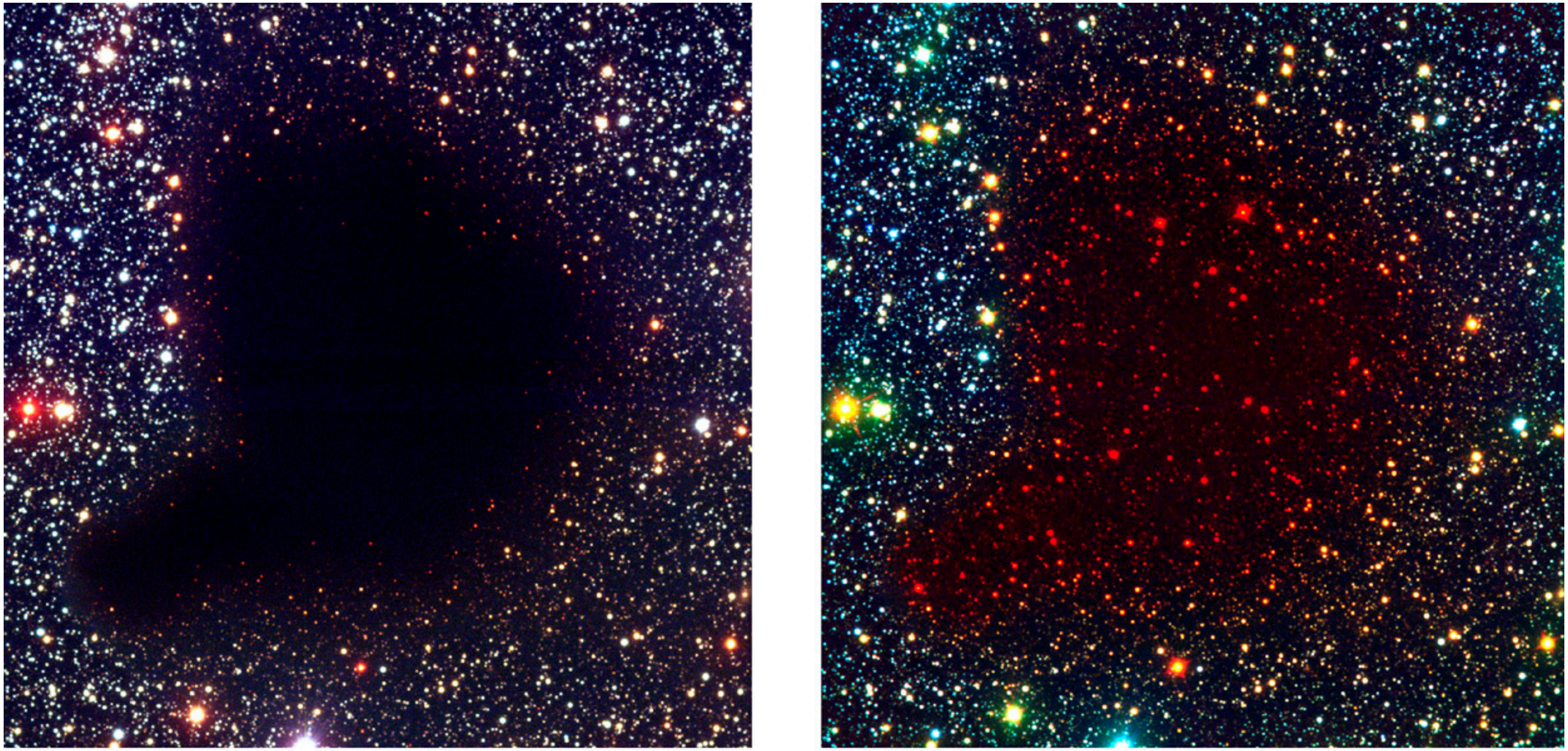


Figure 3.18 Black-body spectra at different temperatures. Each source is of the same size, and at the same distance from the detector that measures the flux density. Note that the vertical scale for the set of spectra in (a) is greatly elongated compared with that for the set in (b).

Wide-field view of the Milky Way



B, V, I B, I, K

Pre-Collapse Black Cloud B68 (comparison)
(VLT ANTU + FORS 1 - NTT + SOFI)

ESO PR Photo 02c/01 (10 January 2001)

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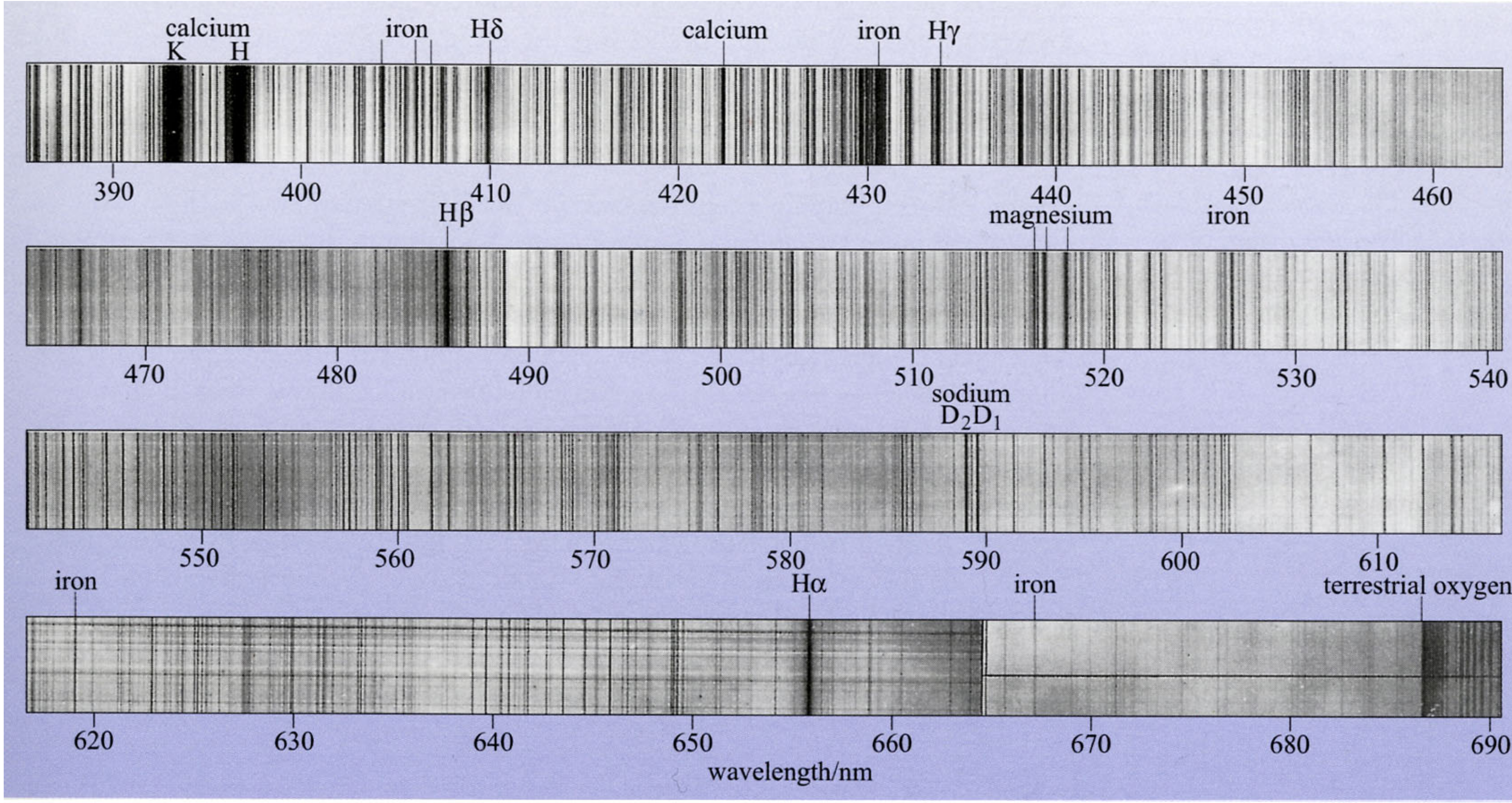


Figure 1.28 A black and white image of the solar spectrum. Note that for convenience of display, the spectrum has been cut into sections and consecutive sections have been stacked vertically in sequence. (The horizontal streaks on the spectra are artefacts.) (Kitt Peak National Observatory)

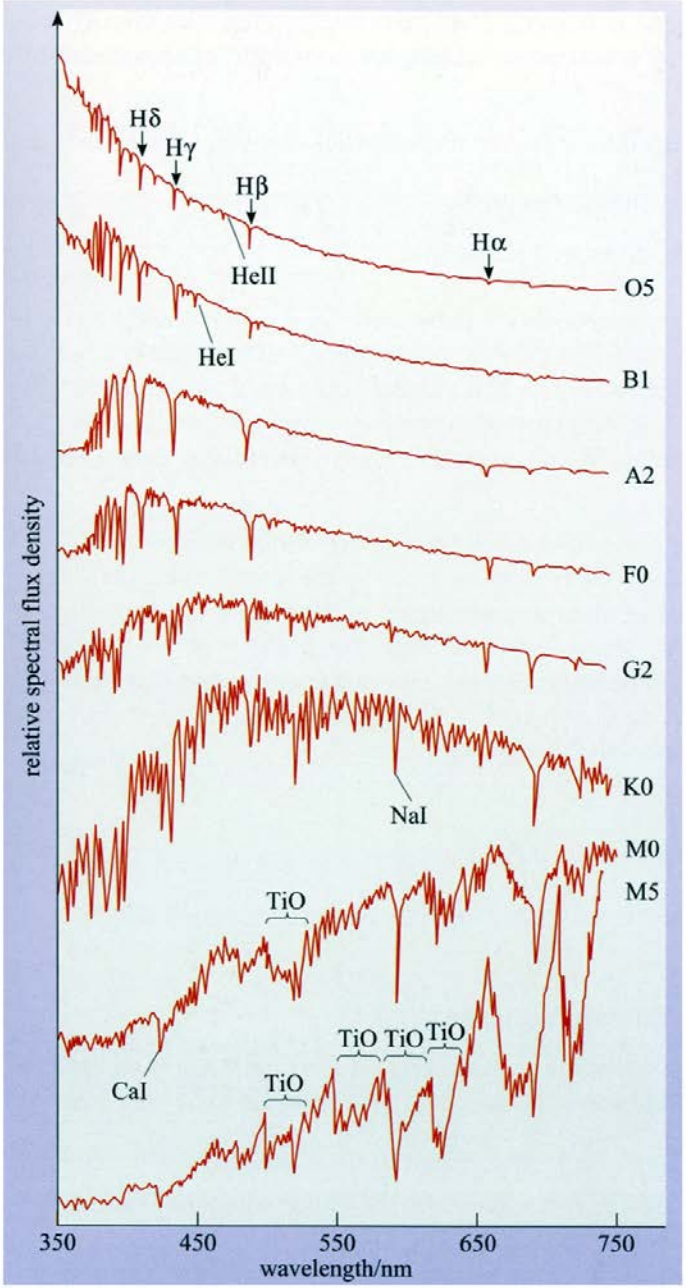
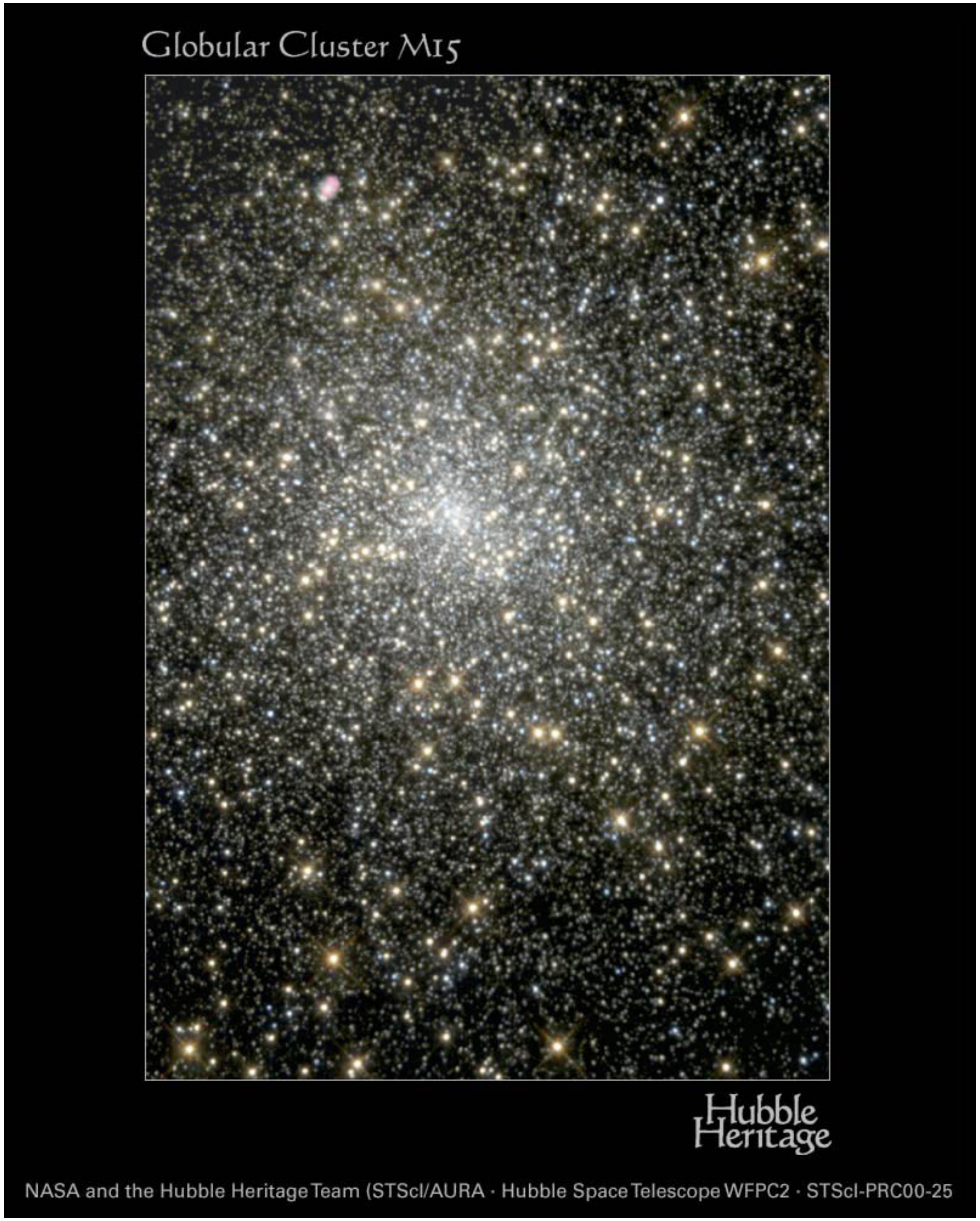


Figure 3.26 The stellar absorption spectra given in Figure 3.25 are more usually presented as graphs of relative flux density versus wavelength for ease of identification of the prominent absorption lines. The spectra have been plotted without spectral flux density scales and displaced vertically for clarity. (Kaufmann and Freedman, 1998)

Star clusters with size << distance allow some progress. Also evidence that Δt_{form} << age, so stars coeval



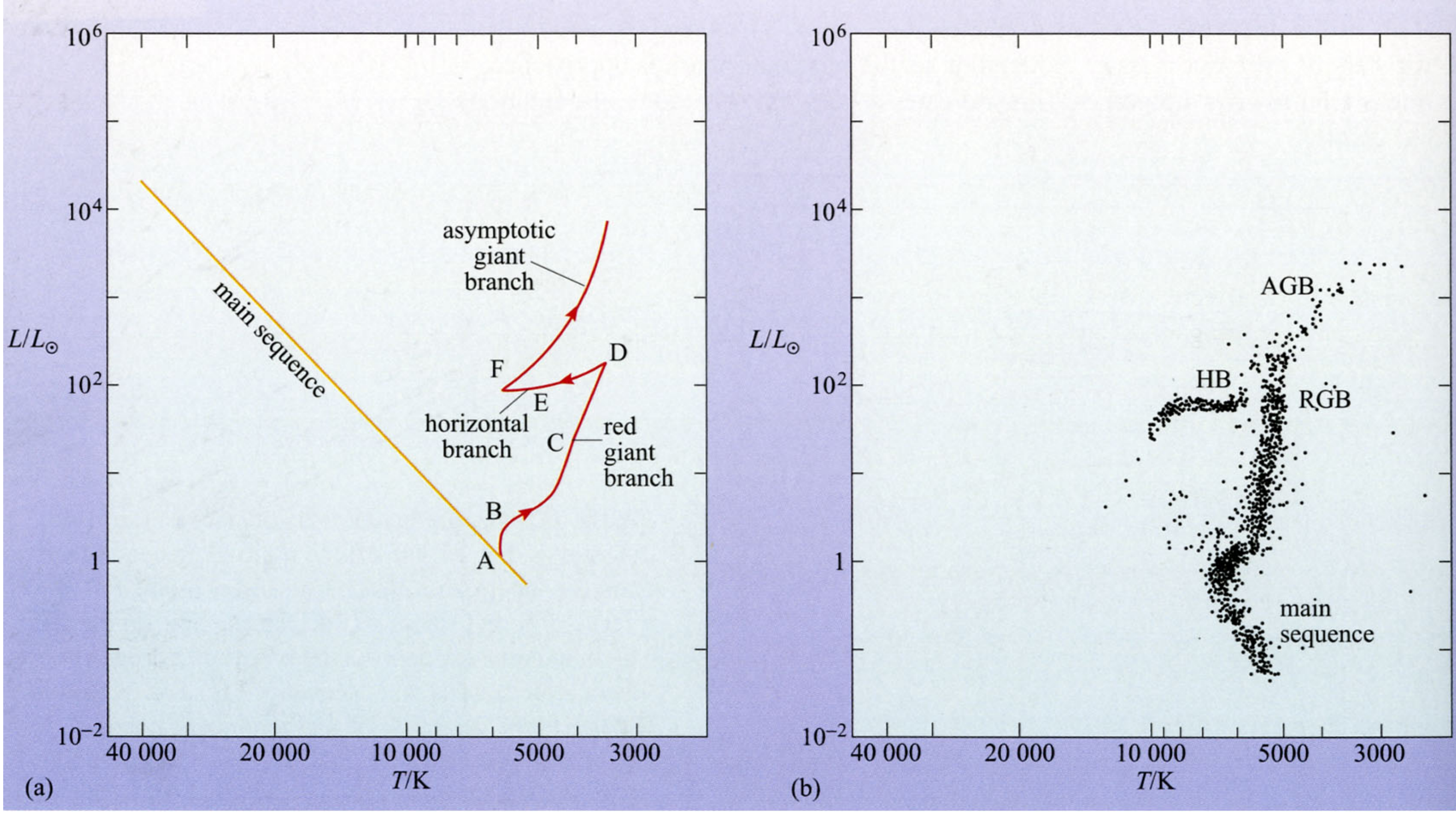
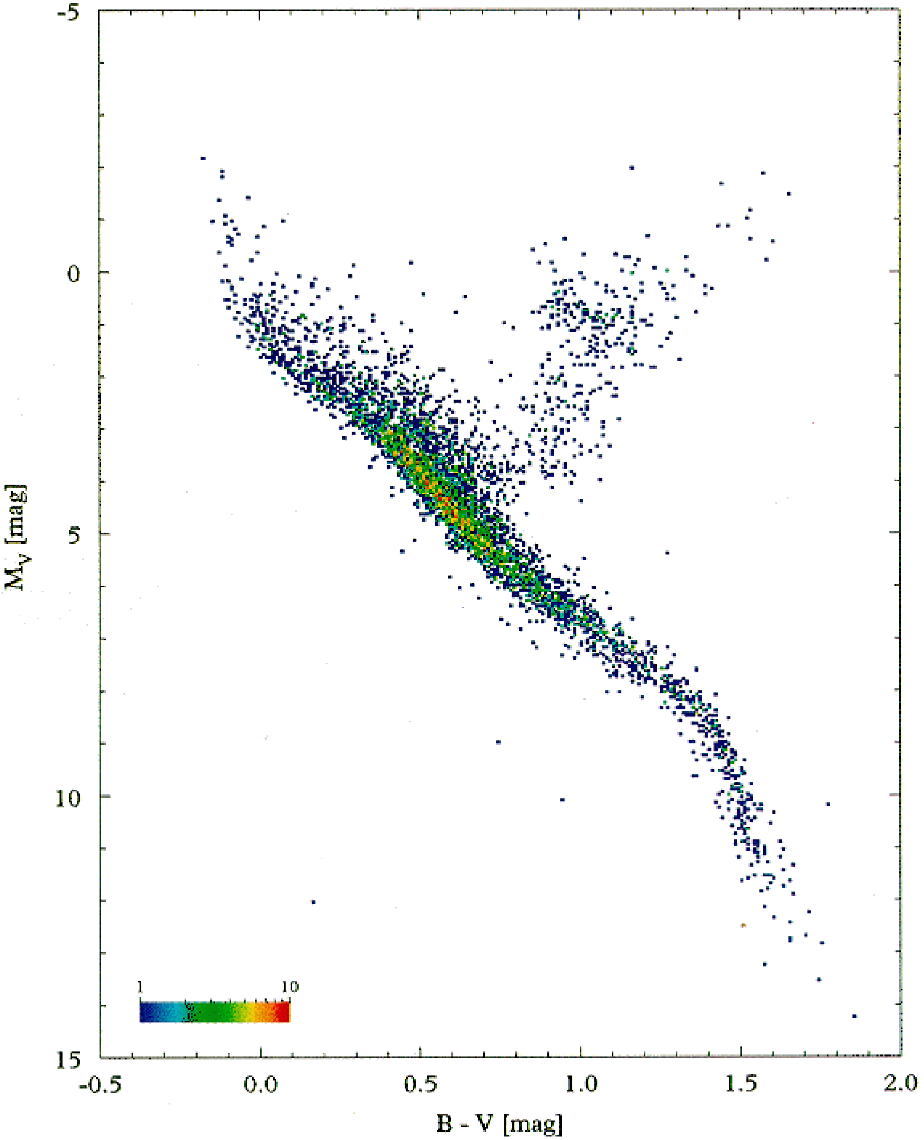


Figure 7.3 (a) The predicted path of a $1 M_\odot$ star, plotted on the same scale with the same labels as Figure 7.2, (A) hydrogen core fusion; (B) onset of hydrogen shell fusion; (C) hydrogen shell fusion continues; (D) helium core fusion starts; (E) helium core fusion continues; (F) helium shell fusion starts. (b) The H–R diagram of a globular cluster which illustrates how stars tend to concentrate in these regions.

HIPPARCOS satellite data showing Hertzsprung-Russell diagram for stars within 150pc of the Sun



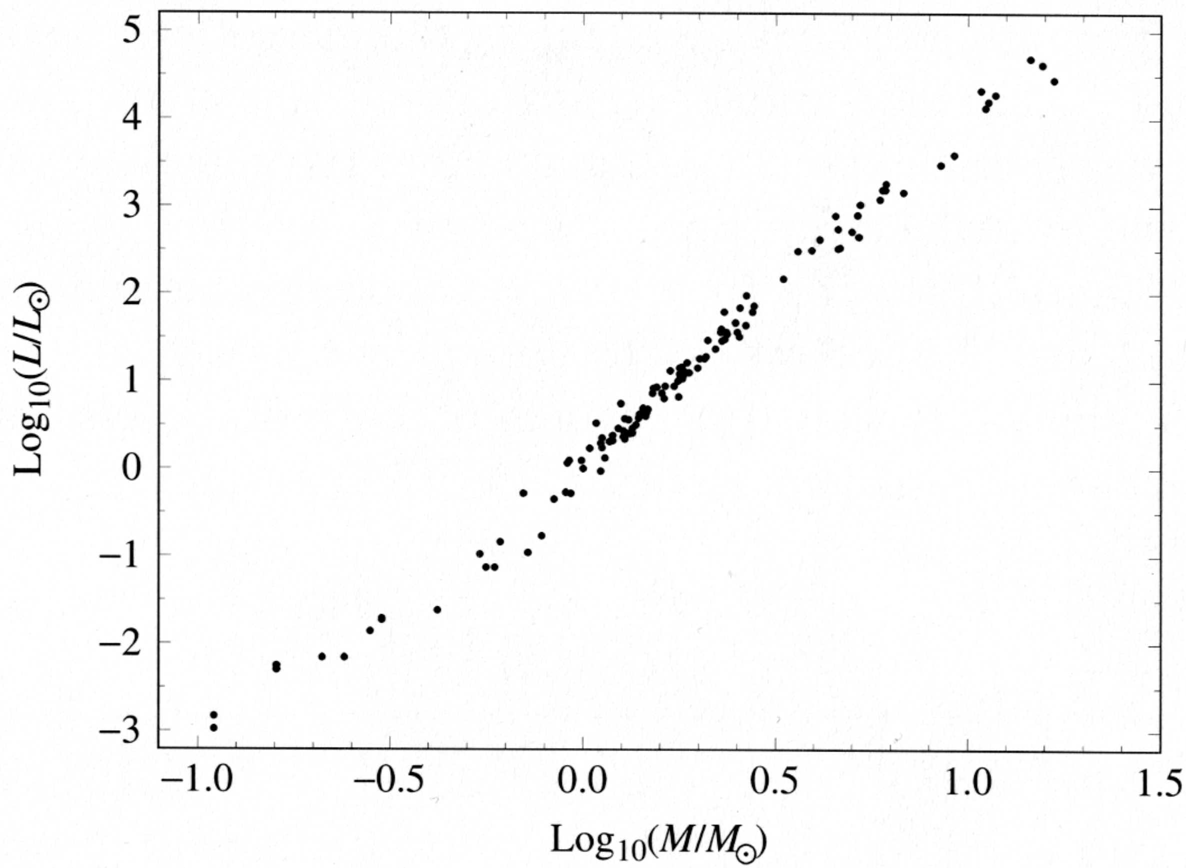
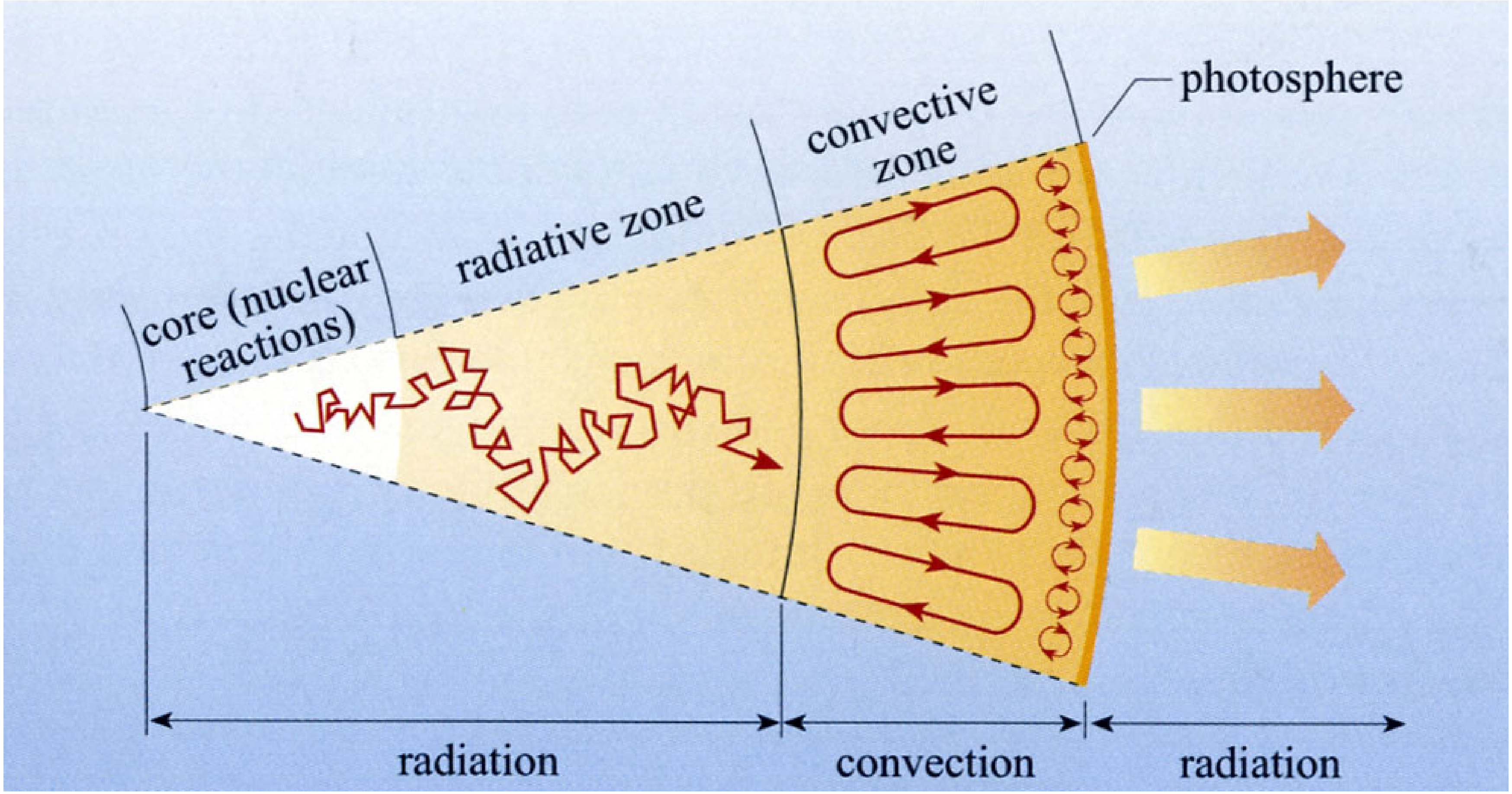
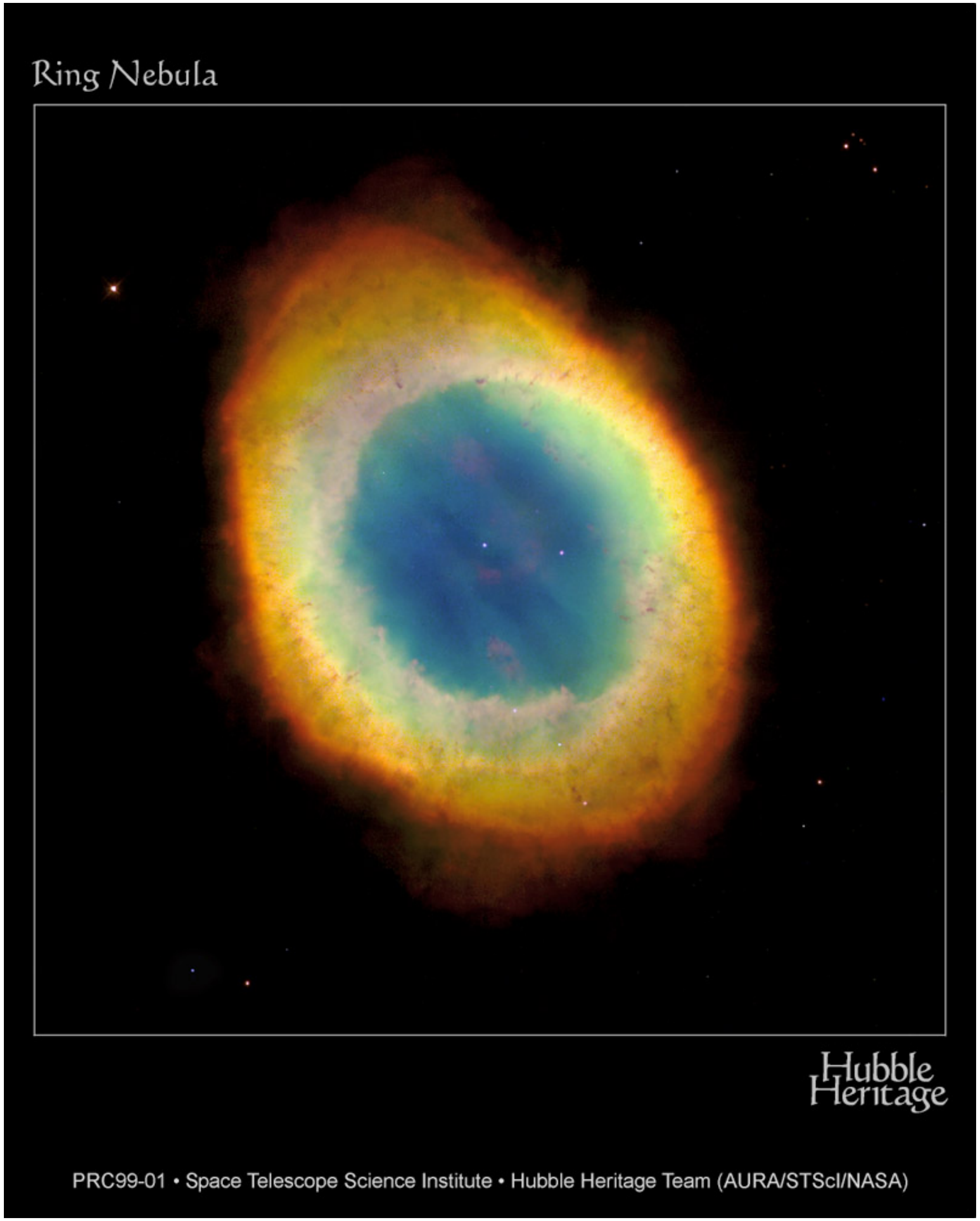
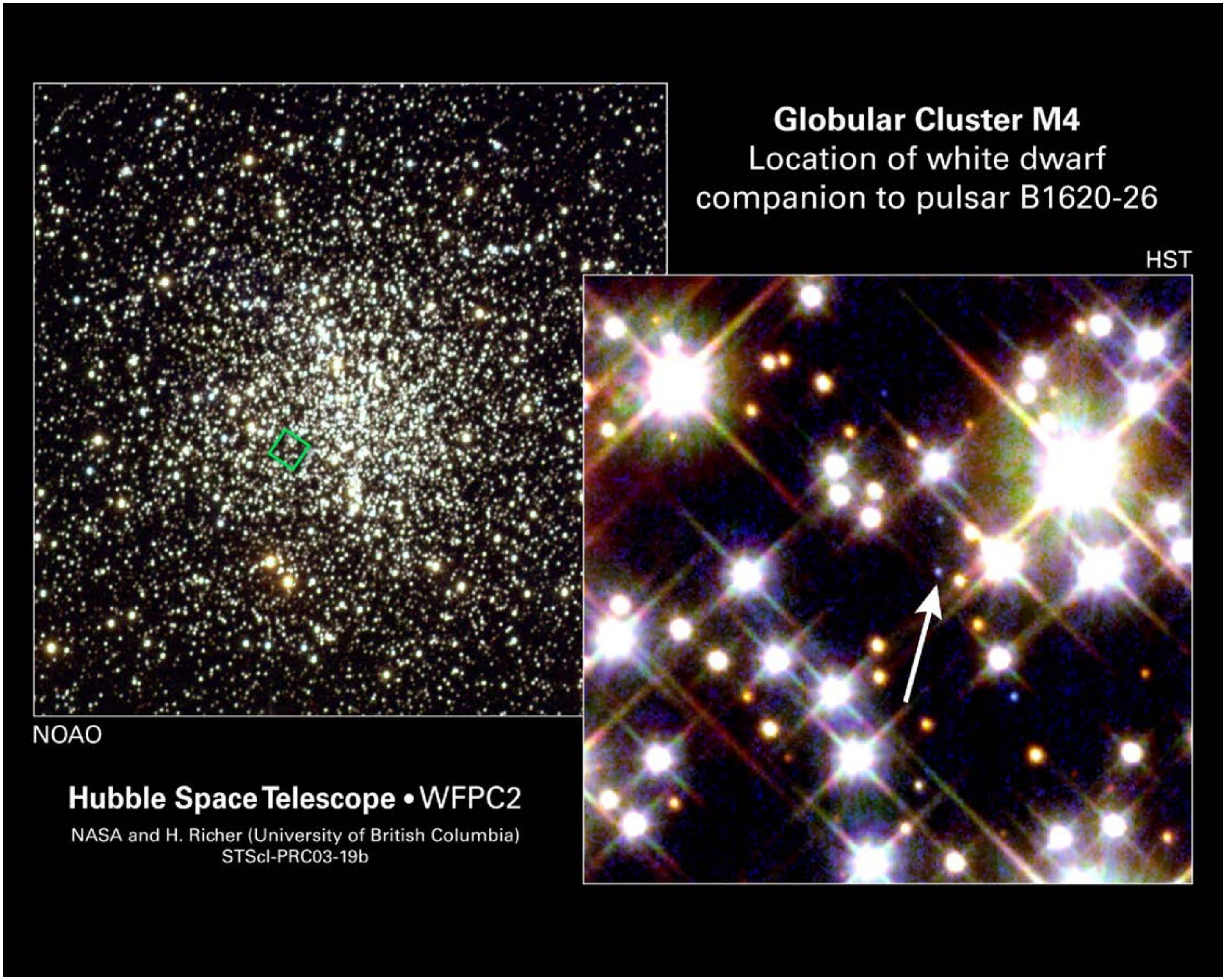


Figure 7.7 The mass–luminosity relation. (Data from Popper, *Annu. Rev. Astron. Astrophys.*, *18*, 115, 1980.)

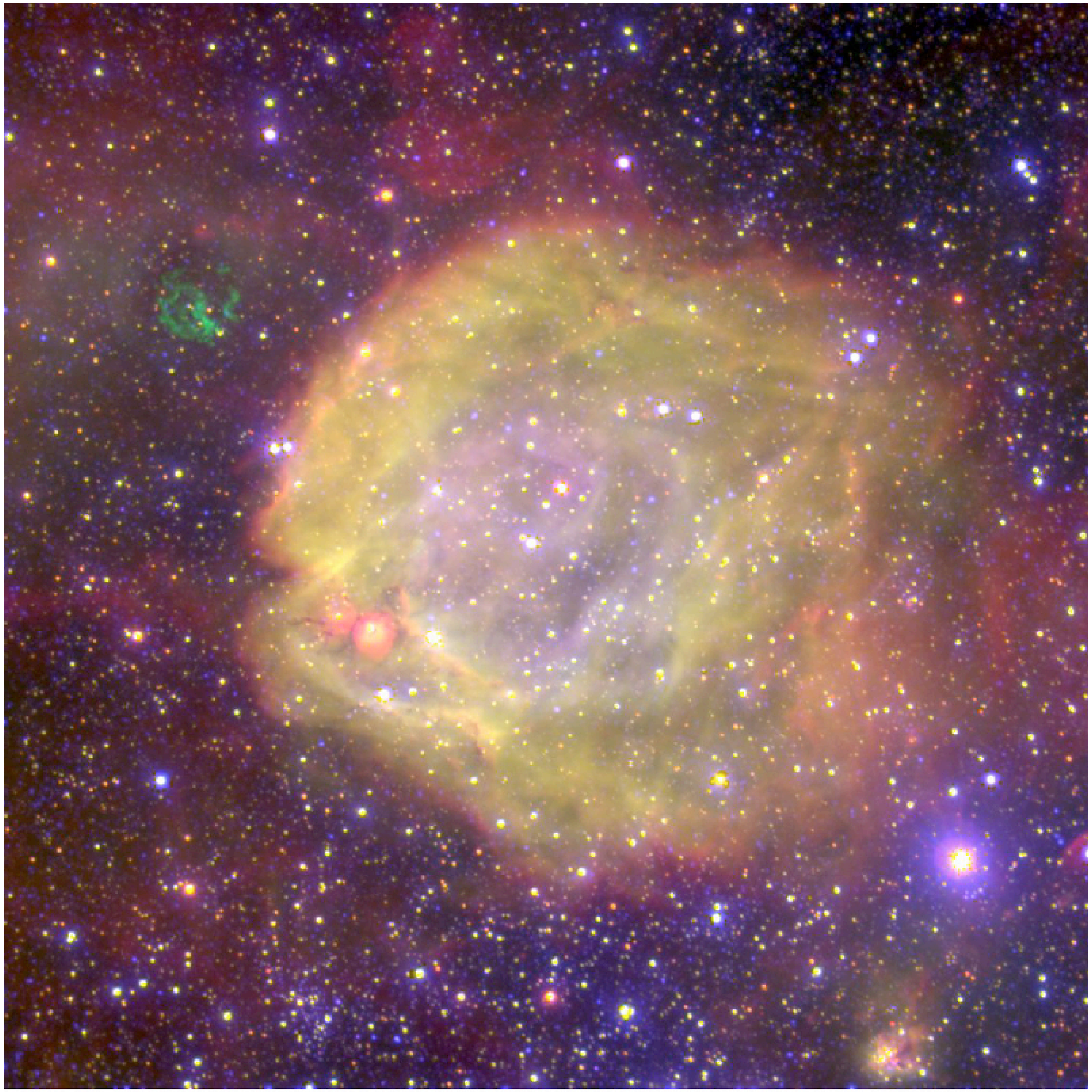

radiative zone
convective zone
core


photosphere
convective zone
radiative zone
core (nuclear reactions)
radiation
convection
radiation


Ring Nebula
Hubble Heritage
PRC99-01 • Space Telescope Science Institute • Hubble Heritage Team (AURA/STScI/NASA)


Globular Cluster M4
Location of white dwarf companion to pulsar B1620-26
HST
NOAO
Hubble Space Telescope • WFPC2
NASA and H. Richer (University of British Columbia)
STScI-PRC03-19b


Cat's Eye Nebula • NGC 6543
Hubble Heritage
NASA, ESA, HEIC and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope ACS • STScI-PRC04-27



Nebula Around the Hot Binary Star AB7 in the SMC
(VLT MELIPAL + FORS 1)

ESO PR Photo 09a/03 (8 April 2003)

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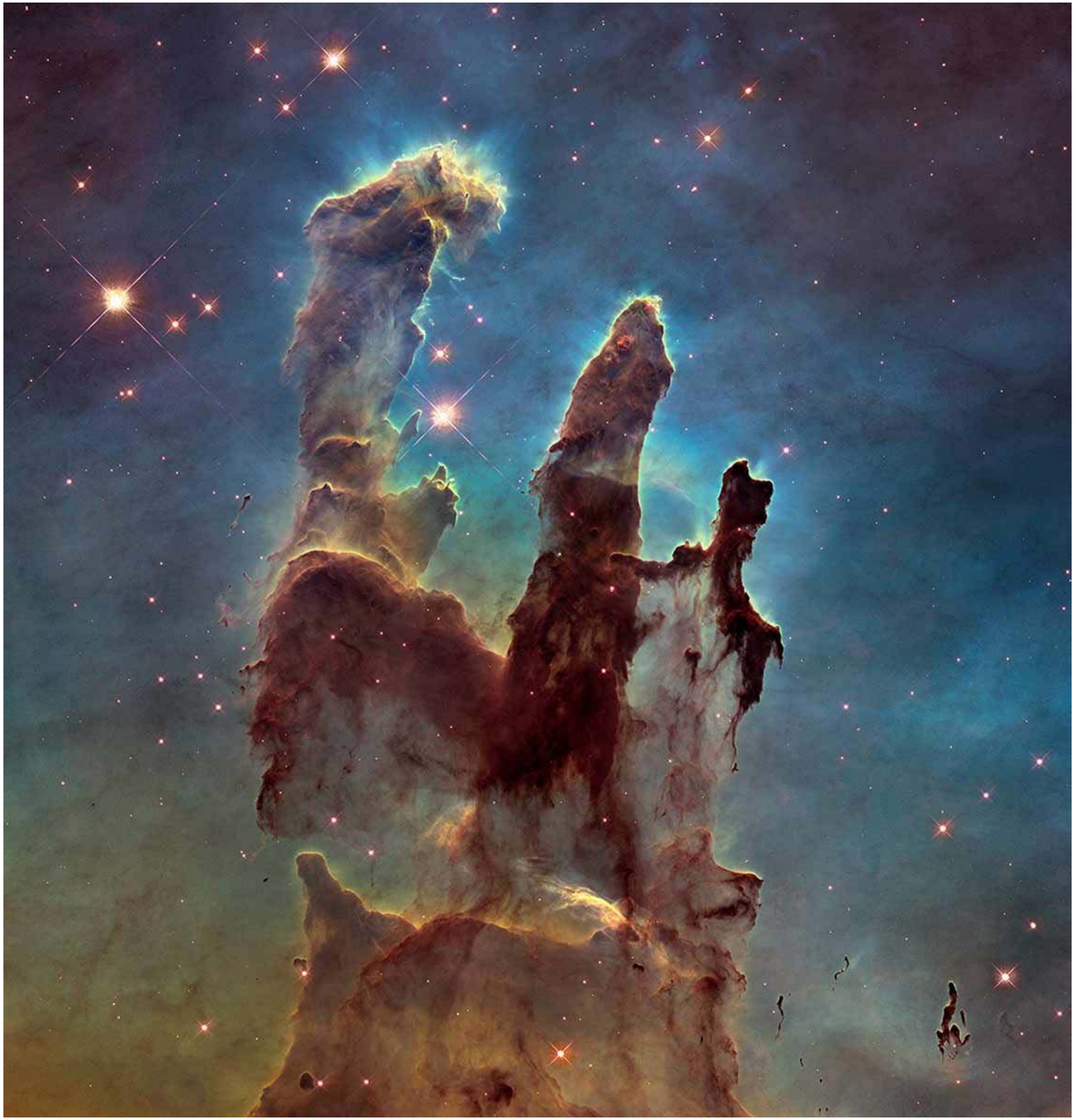
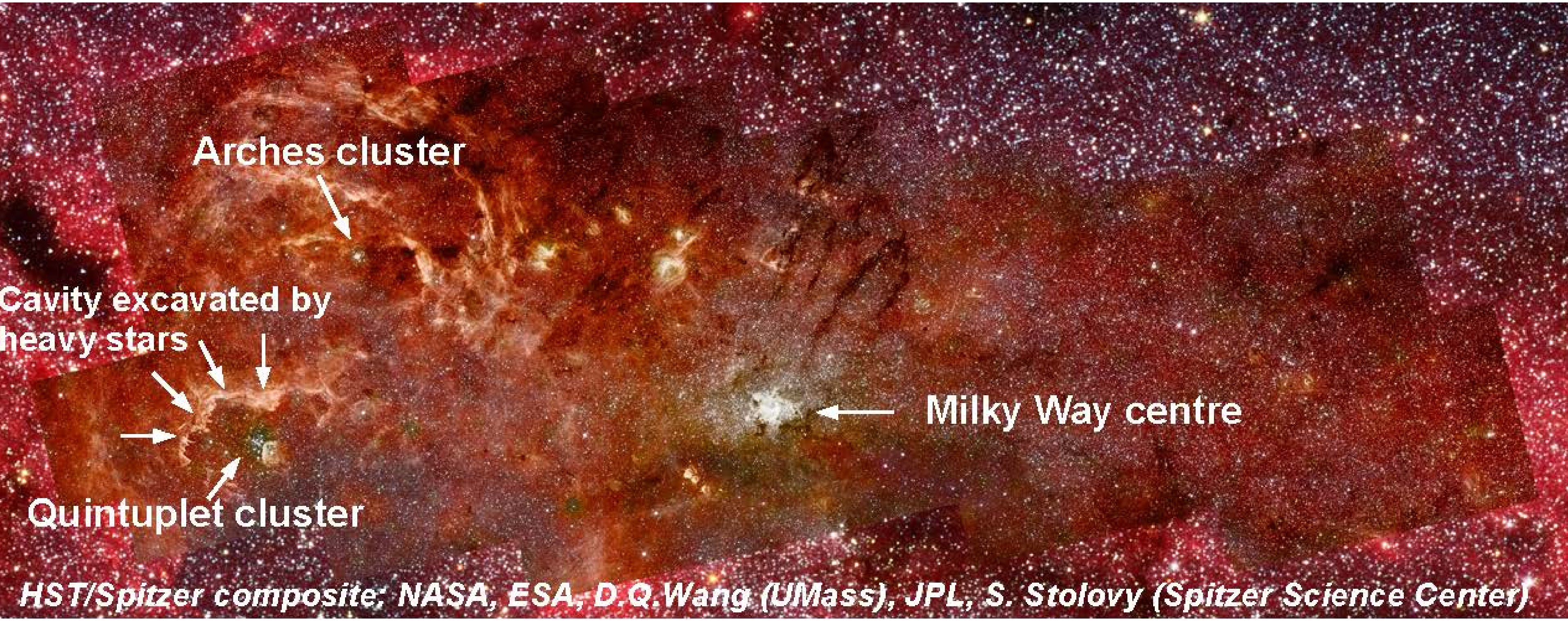
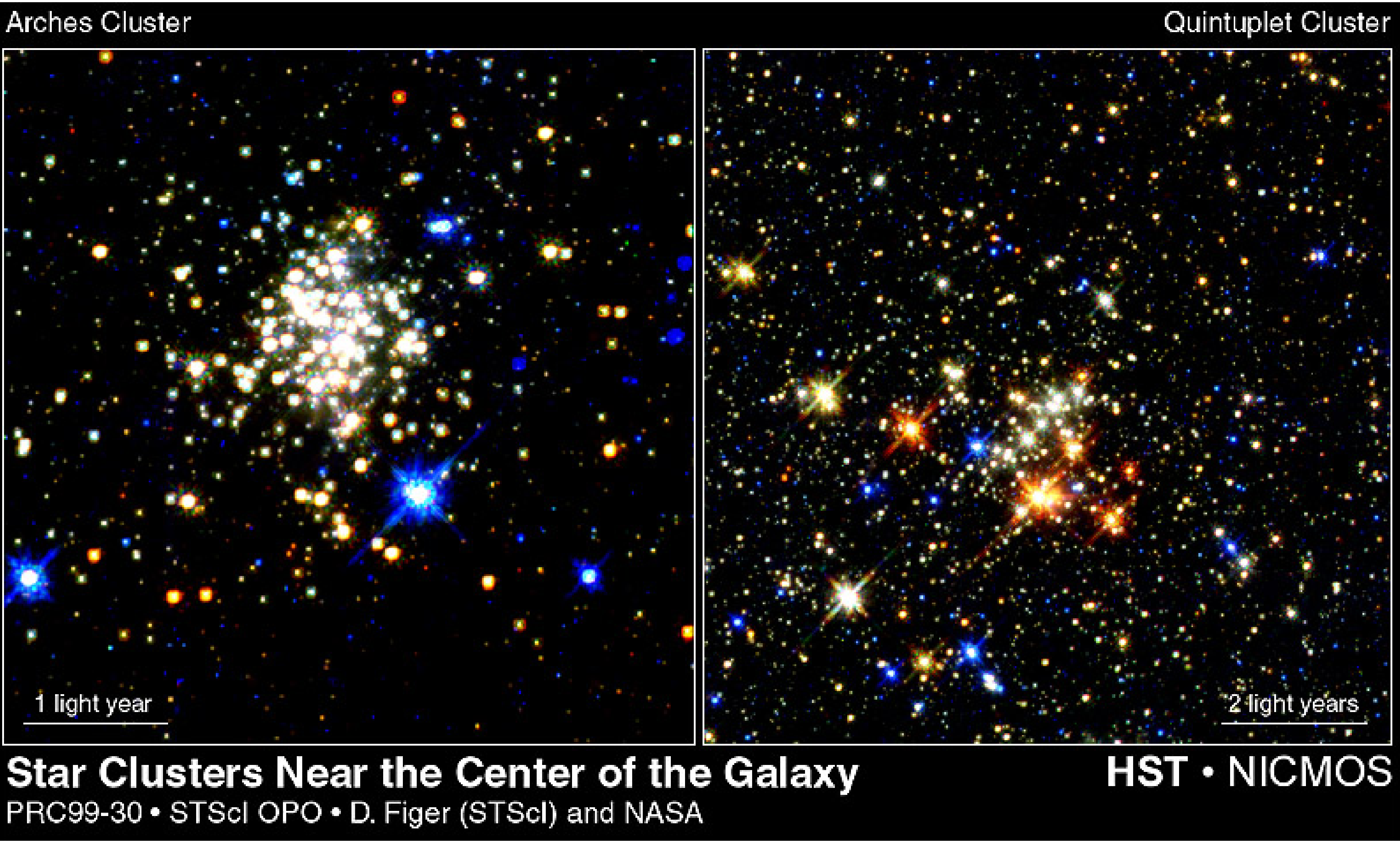


HST


Arches cluster
Cavity excavated by
heavy stars
Milky Way centre
Quintuplet cluster
HST/Spitzer composite; NASA, ESA, D.Q.Wang (UMass), JPL, S. Stolovy (Spitzer Science Center)



Arches Cluster
Quintuplet Cluster
1 light year
2 light years
Star Clusters Near the Center of the Galaxy
HST • NICMOS
PRC99-30 • STScI OPO • D. Figer (STScI) and NASA

Spiral Galaxy NGC 6118 and SN 2004dk
(VLT MELIPAL + VIMOS)

ESO PR Photo 33b/04 (1 December 2004)

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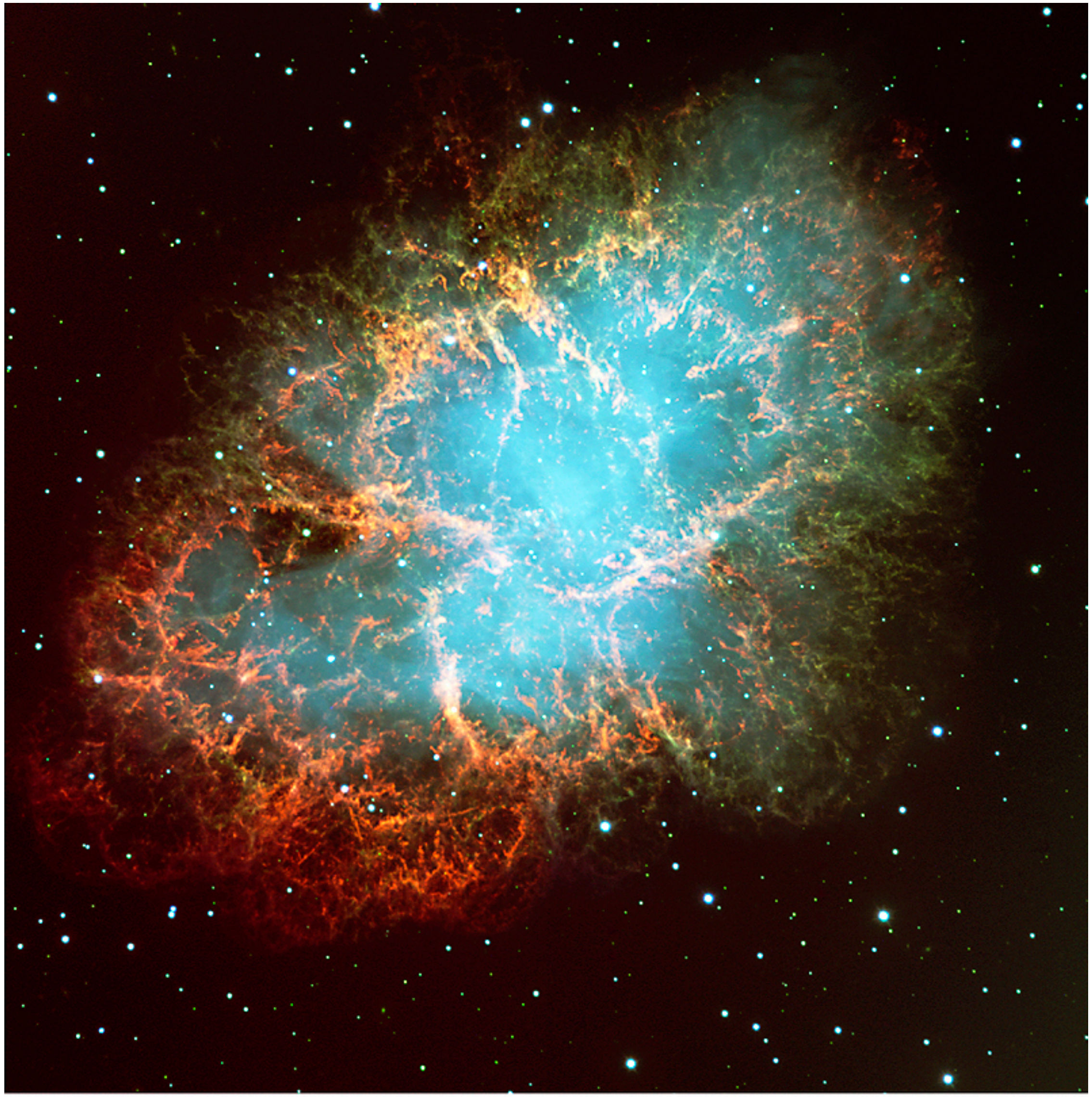
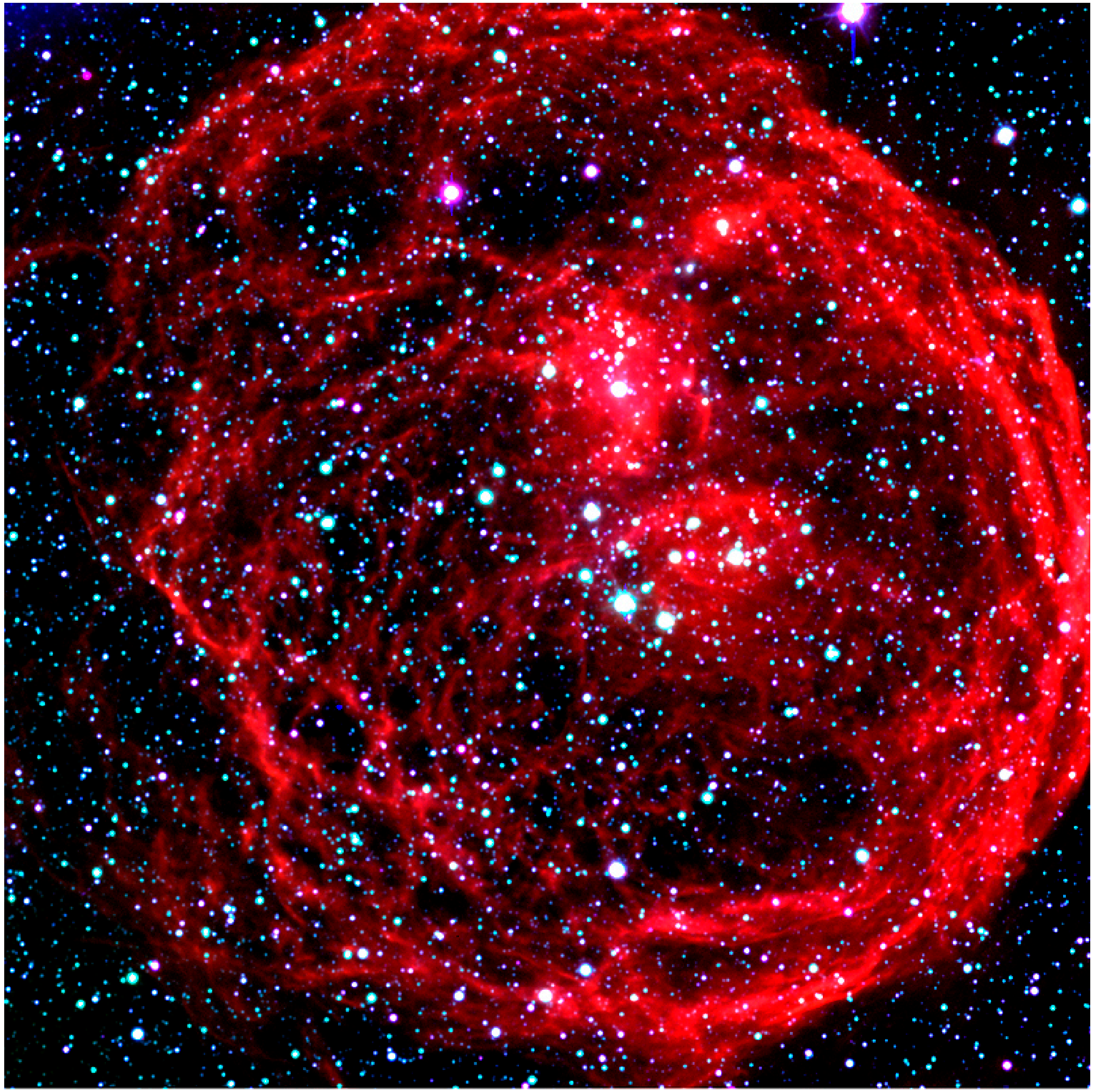


The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

ESO PR Photo 40f/99 (17 November 1999)

© European Southern Observatory



N 70 Nebula in the Large Magellanic Cloud (VLT KUEYEN + FORS2)

ESO PR Photo 40d/99 (17 November 1999)

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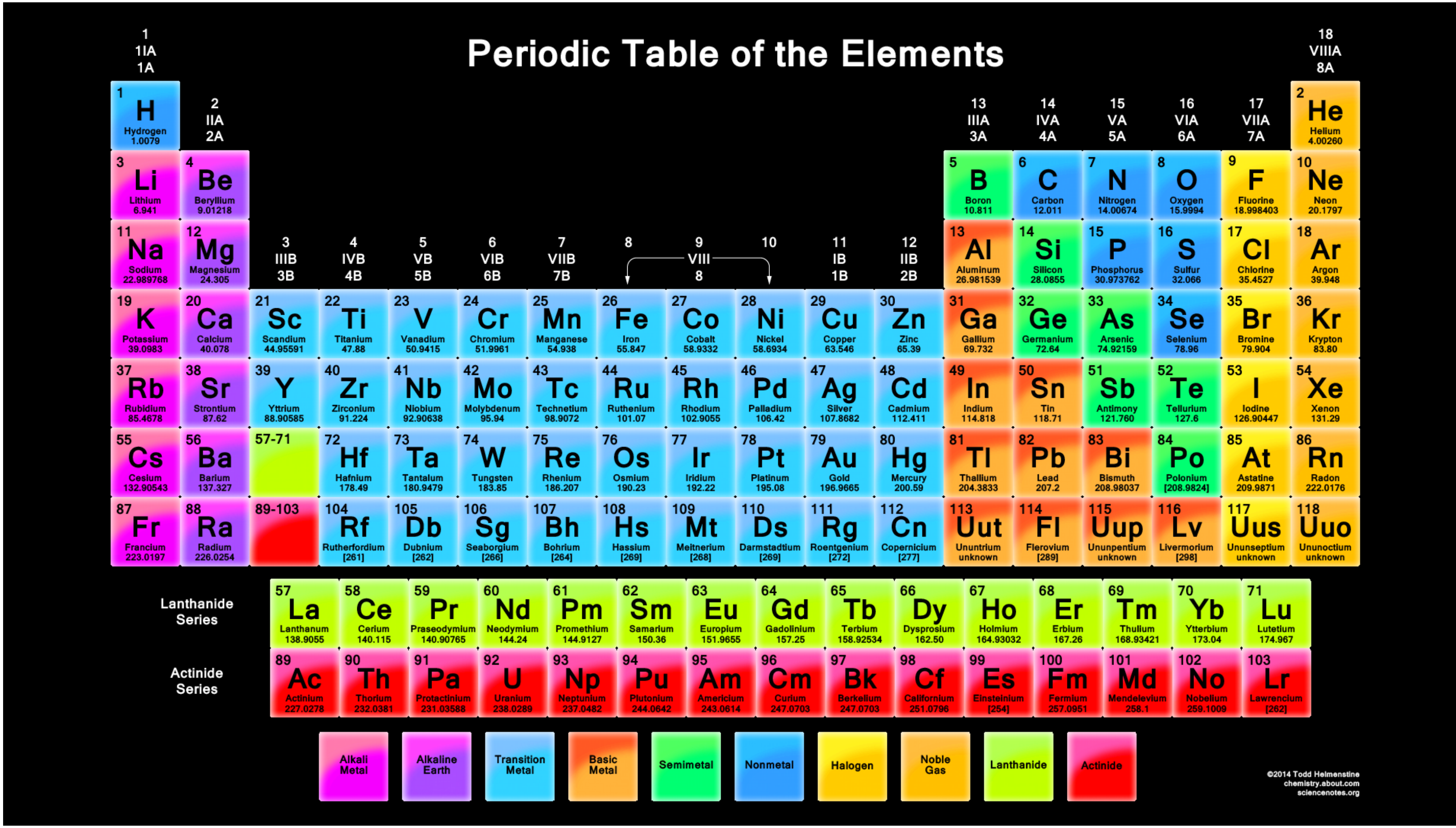
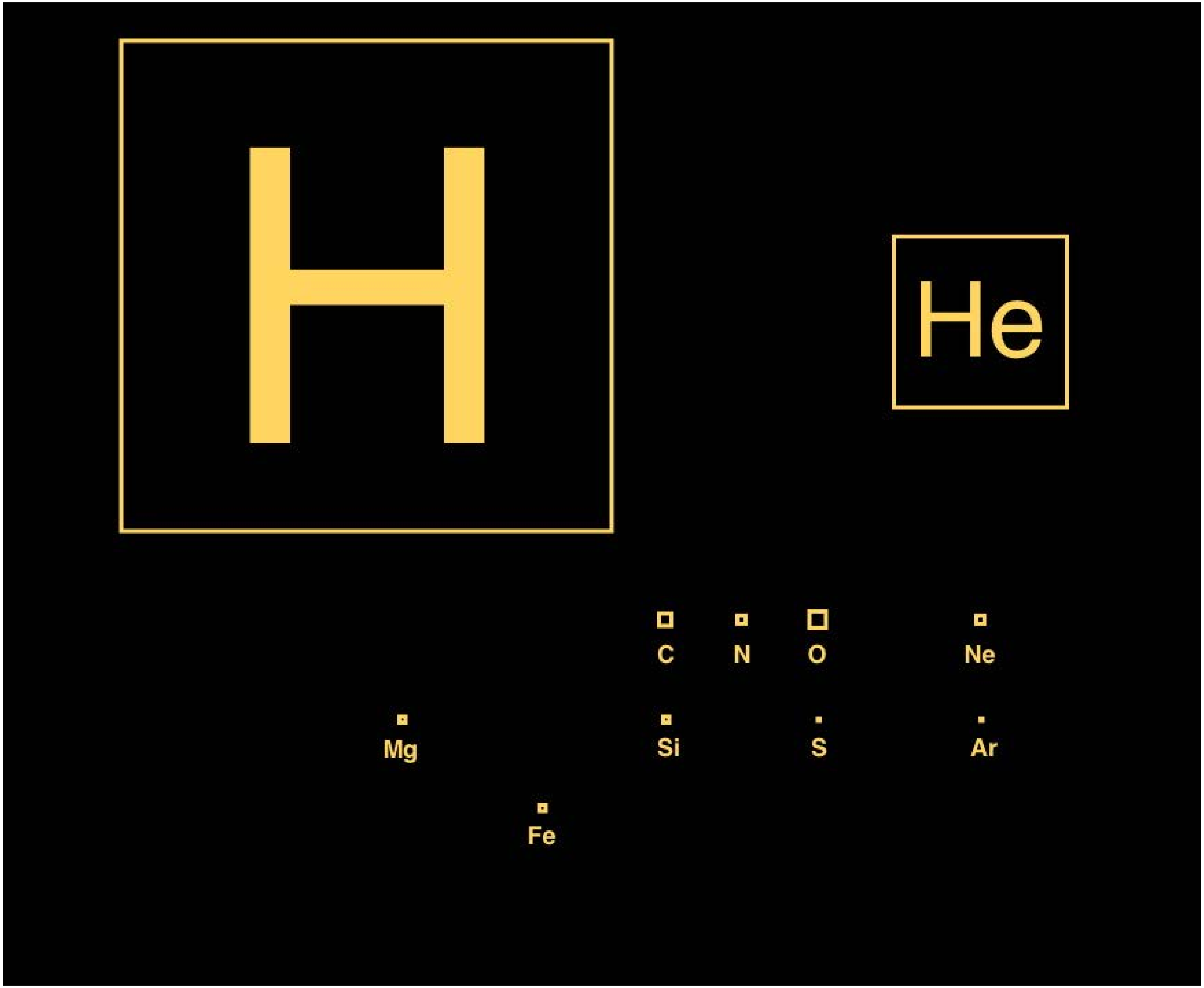
Stars in a wider context: origin of the elements and stellar populations

- Astronomers periodic table
- Post Big Bang – H, He (and tiny fraction of Li)
- Essentially all elements formed in stars
- Everything other than H and He is a “metal”
- Fraction of metals determines the “metallicity” of a system and everything is referenced to the number of H atoms
- Most stars are observed to belong to one of two populations – Population I and Population II
- Two types of massive galaxies – ellipticals and spirals
- Stars can effect galaxies – M82 starburst driven outflows


Periodic Table of the Elements
1 IA 1A
2 IIA 2A
3 IIIB 3B
4 IVB 4B
5 VB 5B
6 VIB 6B
7 VIIB 7B
8 VIII 8
9
10
11 IB 1B
12 IIB 2B
13 IIIA 3A
14 IVA 4A
15 VA 5A
16 VIA 6A
17 VIIA 7A
18 VIIIA 8A
1 H Hydrogen 1.0079
2 He Helium 4.00260
3 Li Lithium 6.941
4 Be Beryllium 9.01218
5 B Boron 10.811
6 C Carbon 12.011
7 N Nitrogen 14.00674
8 O Oxygen 15.9994
9 F Fluorine 18.998403
10 Ne Neon 20.1797
11 Na Sodium 22.989768
12 Mg Magnesium 24.305
13 Al Aluminum 26.981539
14 Si Silicon 28.0855
15 P Phosphorus 30.973762
16 S Sulfur 32.066
17 Cl Chlorine 35.4527
18 Ar Argon 39.948
19 K Potassium 39.0983
20 Ca Calcium 40.078
21 Sc Scandium 44.95591
22 Ti Titanium 47.88
23 V Vanadium 50.9415
24 Cr Chromium 51.9961
25 Mn Manganese 54.938
26 Fe Iron 55.847
27 Co Cobalt 58.9332
28 Ni Nickel 58.6934
29 Cu Copper 63.546
30 Zn Zinc 65.39
31 Ga Gallium 69.732
32 Ge Germanium 72.64
33 As Arsenic 74.92159
34 Se Selenium 78.96
35 Br Bromine 79.904
36 Kr Krypton 83.80
37 Rb Rubidium 85.4678
38 Sr Strontium 87.62
39 Y Yttrium 88.90585
40 Zr Zirconium 91.224
41 Nb Niobium 92.90638
42 Mo Molybdenum 95.94
43 Tc Technetium 98.9072
44 Ru Ruthenium 101.07
45 Rh Rhodium 102.9055
46 Pd Palladium 106.42
47 Ag Silver 107.8682
48 Cd Cadmium 112.411
49 In Indium 114.818
50 Sn Tin 118.71
51 Sb Antimony 121.760
52 Te Tellurium 127.6
53 I Iodine 126.90447
54 Xe Xenon 131.29
55 Cs Cesium 132.90543
56 Ba Barium 137.327
57-71
72 Hf Hafnium 178.49
73 Ta Tantalum 180.9479
74 W Tungsten 183.85
75 Re Rhenium 186.207
76 Os Osmium 190.23
77 Ir Iridium 192.22
78 Pt Platinum 195.08
79 Au Gold 196.9665
80 Hg Mercury 200.59
81 Tl Thallium 204.3833
82 Pb Lead 207.2
83 Bi Bismuth 208.98037
84 Po Polonium [208.9824]
85 At Astatine 209.9871
86 Rn Radon 222.0176
87 Fr Francium 223.0197
88 Ra Radium 226.0254
89-103
104 Rf Rutherfordium [261]
105 Db Dubnium [262]
106 Sg Seaborgium [266]
107 Bh Bohrium [264]
108 Hs Hassium [269]
109 Mt Meitnerium [268]
110 Ds Darmstadtium [269]
111 Rg Roentgenium [272]
112 Cn Copernicium [277]
113 Uut Ununtrium unknown
114 Fl Flerovium [289]
115 Uup Ununpentium unknown
116 Lv Livermorium [298]
117 Uus Ununseptium unknown
118 Uuo Ununoctium unknown
Lanthanide Series
57 La Lanthanum 138.9055
58 Ce Cerium 140.115
59 Pr Praseodymium 140.90765
60 Nd Neodymium 144.24
61 Pm Promethium 144.9127
62 Sm Samarium 150.36
63 Eu Europium 151.9655
64 Gd Gadolinium 157.25
65 Tb Terbium 158.92534
66 Dy Dysprosium 162.50
67 Ho Holmium 164.93032
68 Er Erbium 167.26
69 Tm Thulium 168.93421
70 Yb Ytterbium 173.04
71 Lu Lutetium 174.967
Actinide Series
89 Ac Actinium 227.0278
90 Th Thorium 232.0381
91 Pa Protactinium 231.03588
92 U Uranium 238.0289
93 Np Neptunium 237.0482
94 Pu Plutonium 244.0642
95 Am Americium 243.0614
96 Cm Curium 247.0703
97 Bk Berkelium 247.0703
98 Cf Californium 251.0796
99 Es Einsteinium [254]
100 Fm Fermium 257.0951
101 Md Mendelevium 258.1
102 No Nobelium 259.1009
103 Lr Lawrencium [262]
Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Semimetal
Nonmetal
Halogen
Noble Gas
Lanthanide
Actinide
©2014 Todd Helmenstine
chemistry.about.com
sciencenotes.org


H
He
C
N
O
Ne
Mg
Si
S
Ar
Fe

Stellar Populations: Metallicity

- Metallicity is measured relative to the metallicity of the Sun:

$$\left[\mathrm{A/X}\right] = \log_{10}\left(\frac{N_A}{N_X}\right) - \log_{10}\left(\frac{N_A}{N_X}\right)_{sun}$$

- By definition, for the Sun:

$$\left[\mathrm{Fe/H}\right] = 0$$

- Stars with twice solar and 1/10th solar metallicities have:

$$\left[\mathrm{Fe/H}\right] = +0.3; \quad \left[\mathrm{Fe/H}\right] = -1.0$$

- "Young" metal rich Population I stars have:

$$\left[\mathrm{Fe/H}\right] \sim 0$$

- "Old" metal poor Population II stars have:

$$\left[\mathrm{Fe/H}\right] \approx -2$$

Stellar Populations: Metallicity Definitions

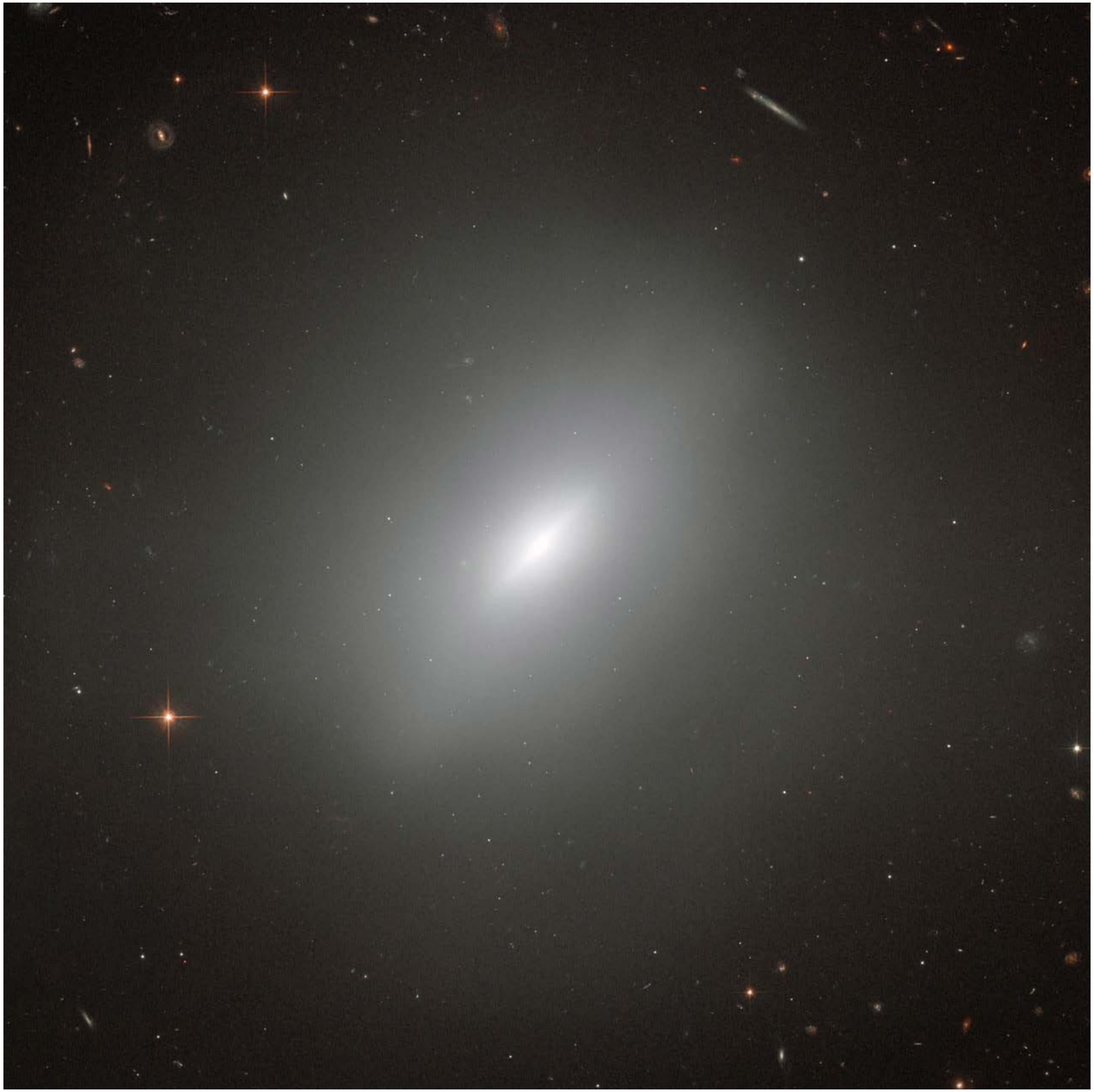
• Conventionally (as in the Table in Examples 2 Q8), abundances are given as the *number* of atoms of element X per Hydrogen atom with the addition of a constant "12"

$$\log_{10}[X/H]+12$$

• By definition, the number abundance of hydrogen is thus =12. For helium, with one helium atom per 10 hydrogen atoms the abundance is =11

$$\log_{10}[He/H]+12\approx 11$$

Optical image of NGC1132 ~400 kpc on a side



M74, probably similar to our own Galaxy – spiral arms with young Population I stars, nuclear bulge with old but metal rich Population II stars. Halo of old metal-poor Population II

Stellar Populations: Metallicity

• The Sun is a typical Population I star, formed from gas that has experienced a number of generations/cycles of enrichment by massive stars and Type I supernovae. Population I stars comprise the stellar content of the disk of our Galaxy, with ages <9Gyr (white dwarf age for Galactic Disk – Lecture 19)

• The Halo of our Galaxy is made up predominantly of Population II stars that also have some evidence for enrichment from massive stars, although many of the stars possess only 1/100th of the heavy metals present in Population I stars like the Sun. Age of the Population II stars is ~11-13 Gyr, almost as old as the universe

• Observations of high-redshift objects (very early times), even quasars, show direct evidence for early enrichment of gas due to nuclear burning in stars

Hubble optical near-IR composite with outflow visible in the light of ionized hydrogen

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