# Nuclear Astrophysics

Lecture 1

Thurs. Oct 20, 2011

Prof. Shawn Bishop, Office 2013,

Ex. 12437

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# Reading and References

- *Cauldrons in the Cosmos: Nuclear Astrophysics*, C.E. Rolfs & W. S. Rodney, University Of Chicago Press
- *Principles of Stellar Evolution and Nucleosynthesis*, Donald D. Clayton, University Of Chicago Press
- *Nuclear Physics of Stars*, Christian Iliadis, Wiley-VCH
- *Nucleosynthesis and Chemical Evolution of Galaxies*, Bernard E.J. Pagel, Cambridge University Press
- *Supernovae and Nucleosynthesis*, David Arnett, Princeton University Press
- *An Introduction to Modern Astrophysics*, Bradley W. Carroll & Dale A. Ostlie, Addison Wesley
- *Isotopes: Principles and Applications*, Gunter Faure & Teresa M. Mensing, Johen Wiley & Sons, Inc.

# Your Tutor: Peter Ludwig


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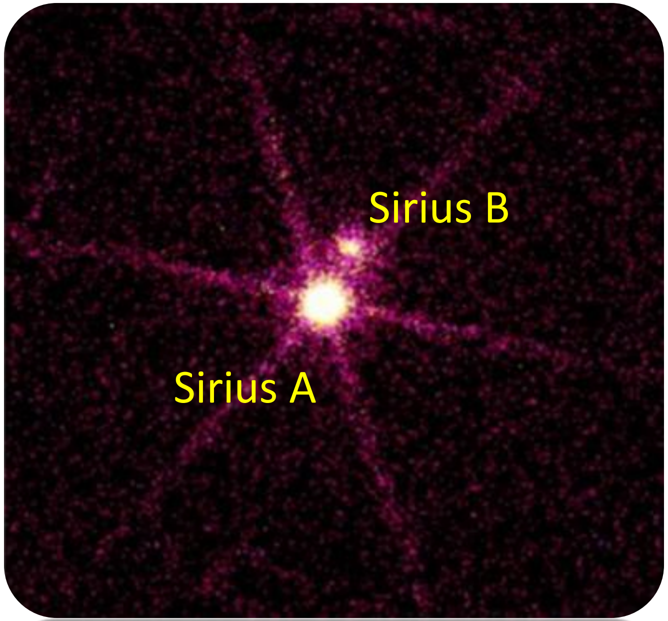
Twinkle, Twinkle Little Star.....

# INTRODUCTION TO THE STARS

# Introduction to the Stars

- ~30% of all stars in multiple systems
- Multiple systems vary from binaries, to Open Clusters, up to the enigmatic Globular Clusters
- Open Clusters: a few to hundreds of stars
- Globular Clusters: ~ $10^5$ stars
- OC's reside in the Galactic Disk; GC's reside in Galactic Halo




Sirius A/B Binary star system
Courtesy: Chandra X-Ray Telescope

# Virial Theorem

Consider point particle, mass $m_i$ and position vector $\mathbf{r}_i$ inside cloud of similar particles. Then equation of motion for any particle *i* is:

$$\frac{d}{dt}\mathbf{p}_i = \mathbf{f}_i$$

Now consider $\sum_i \mathbf{p}_i \cdot \mathbf{r}_i$ and take its time derivative:

$$\frac{d}{dt}\sum_i \mathbf{p}_i \cdot \mathbf{r}_i = \sum_i \frac{d\mathbf{p}_i}{dt} \cdot \mathbf{r}_i + \sum_i \mathbf{p}_i \cdot \frac{d\mathbf{r}_i}{dt}$$

$$= \sum_i \mathbf{f}_i \cdot \mathbf{r}_i + 2K$$

LHS = $\frac{d}{dt}\sum_i m_i \frac{d\mathbf{r}_i}{dt} \cdot \mathbf{r}_i = \frac{d}{dt}\sum_i \frac{1}{2}\frac{d}{dt}(m_i r_i^2) = \frac{1}{2}\frac{d^2 I}{dt^2},\ I = \sum_i m_i r_i^2$

$$I \equiv \text{ moment of inertia of the system}$$

As the system evolves over a long period of time, and settles down into a static configuration, $\frac{d^2}{dt^2} I \rightarrow 0$ leaving us with

$$K = -\frac{1}{2} \sum_i \mathbf{f}_i \cdot \mathbf{r}_i$$

$f_i$ is the force acting on mass $m_i$ from all the other particles in the cloud. Thus, with $\mathbf{F}_{ij}$ the force between particle pairs:

$$\mathbf{f}_i = \sum_{j \neq i} \mathbf{F}_{ij}$$

Also, $\mathbf{F}_{ij} = -\mathbf{F}_{ji}$ (Newton's 3rd Law).

So:

$$K = -\frac{1}{2} \sum_i \left( \sum_{j \neq i} \mathbf{F}_{ij} \right) \cdot \mathbf{r}_i = -\frac{1}{2} \sum_i \left[ \frac{1}{2} \sum_{j \neq i} (\mathbf{F}_{ij} - \mathbf{F}_{ji}) \right] \cdot \mathbf{r}_i$$

$$= -\frac{1}{2} \sum_i \left[ \frac{1}{2} \sum_{j \neq i} \mathbf{F}_{ij} \cdot (\mathbf{r}_i - \mathbf{r}_j) \right]$$

$$= -\frac{1}{2} \sum_i \sum_{j < i} \mathbf{F}_{ij} \cdot (\mathbf{r}_i - \mathbf{r}_j)$$

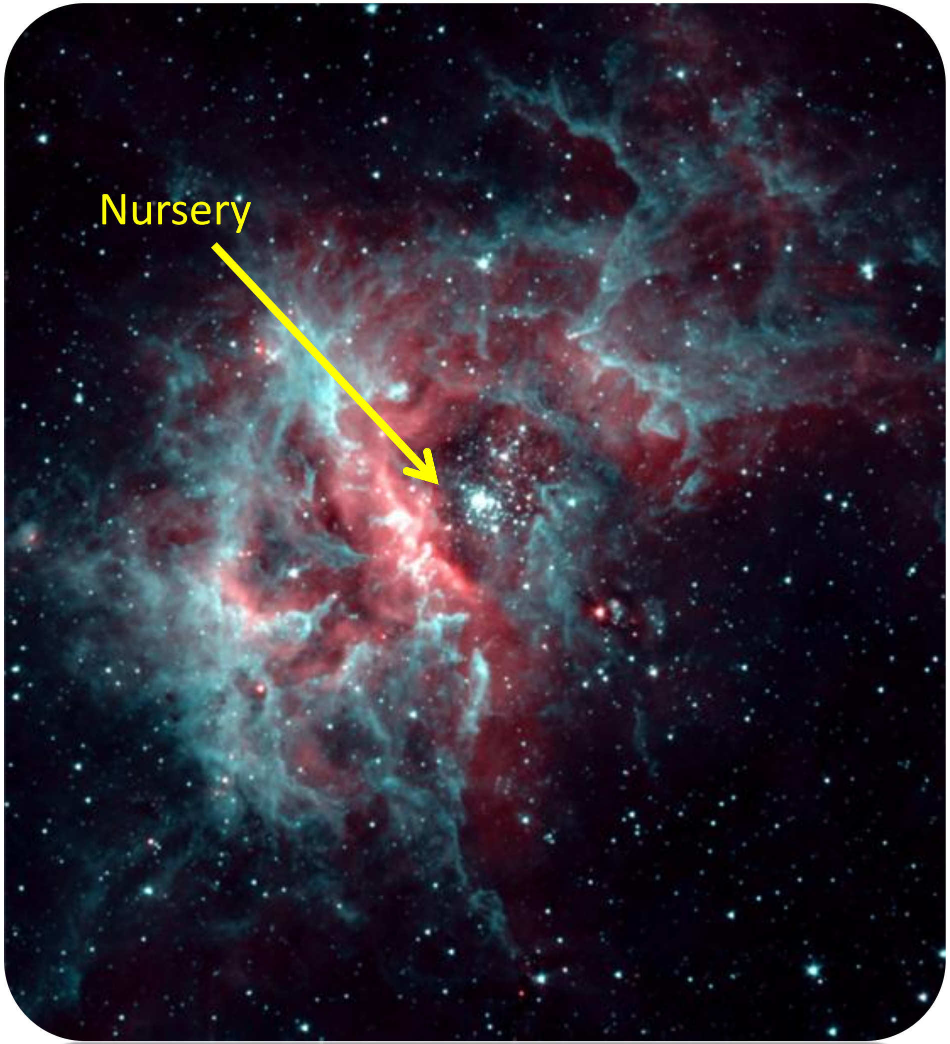
With $\mathbf{F}_{ij} = G\frac{m_i m_j}{r_{ij}^2}\widehat{\mathbf{r}}_{ij}, \mathbf{r}_{ij} = \mathbf{r}_i - \mathbf{r}_j$ , we finally have

$$K = -\frac{1}{2}G\sum_i\sum_{j\neq i}\frac{m_i m_j}{r_{ij}} = -\frac{1}{2}\Omega$$

- For ideal gas: K is related to temperature
- Under collapse, cloud's $\Omega$ increases, resulting in increasing temperature
- Initially, this heat will radiate to space (diffuse gas)
- Eventually, as density increases, however, much heat remains trapped, and temperature increases

# Concept of Stellar Birth

1. Stars are born of "seed" gas undergoing localized gravitational collapse
2. $1^{st}$ generation stars: gas would have been primordial: H and He
3. Later generations formed of processed gas
4. Points 2 & 3 suggest possibility of 2 populations of stars: very old and young
5. Point 4 suggests populations should have different abundance distributions




Spitzer Space Telescope

# Stellar Populations

- Population I (Pop I): Stars that are "metal-rich". Relatively "young" stars as compared to Galactic and Primordial Ages
- Population II (Pop II): Stars that are "metal-poor". *Ancient* relics of the initial star formation periods of Galaxies and first generation of primordial stars
- Metals: any element $A > 4$; that is, any element with $Z > 2$

# The Pleiades Open Cluster (Pop I)

# M30: Globular Cluster (Pop II)

# Schematic of Galaxy of Pop Locations

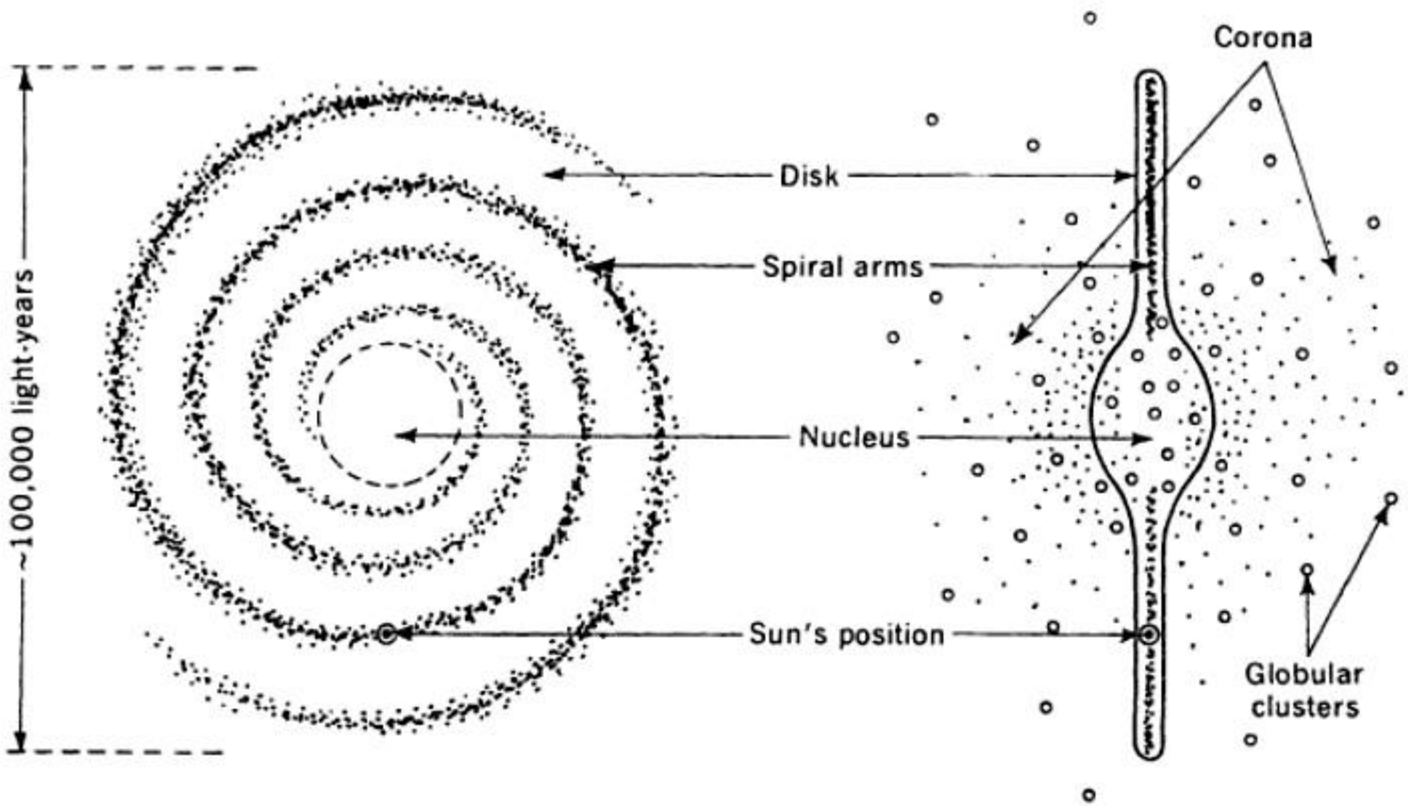



**Fig. 1-13** Schematic representation of the galaxy. (*G. Abell, "Exploration of the Universe," Holt, Rinehart and Winston, Inc., New York,* 1964.)

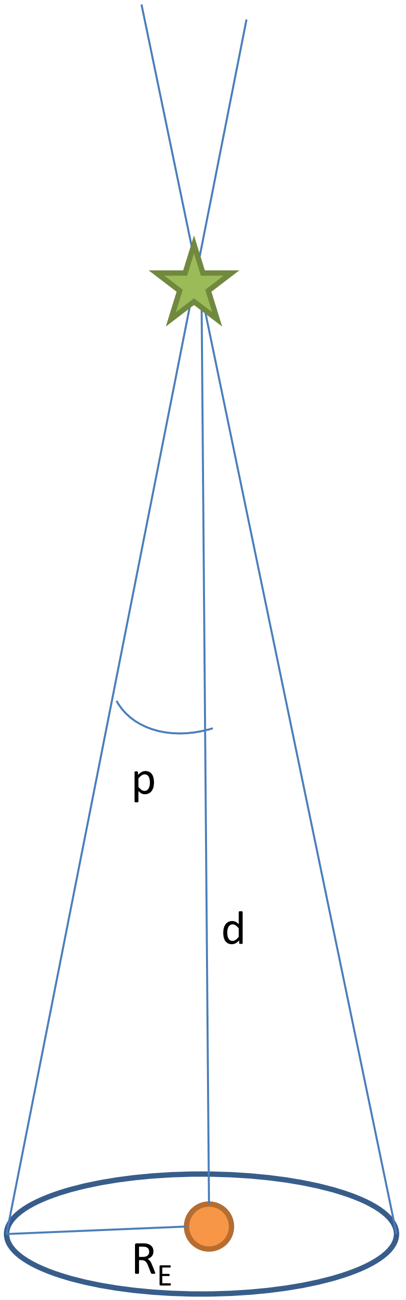
# Stellar Magnitude

For "near" stars, method of parallax can be used to determine distance.

$$d = \frac{R_E}{\tan p} \approx \frac{1}{p} \text{ AU}$$

Astronomers use the unit of parsec to measure stellar distance. A parsec (pc) is the distance such that angle p is equal to 1" of degree (1/3600 degree). 1 AU = 1.49 x $10^{11}$ m

$$\begin{aligned} 1 \text{ pc} &= 3.086 \times 10^{16} \text{ m} \\ &= 3.2616 \text{ lyr} \end{aligned}$$



- Greek astronomer Hipparchus was one of the first skywatchers to systematically catalogue the ~850 stars he observed
- He assigned a magnitude index to each star ranging from m=1, for the brightest stars, to m=6 for the dimmest (opposite ordering of what one would expect)
- Human eye has a nearly logarithmic subjective response to radiant energy flux
- Modern astronomy defines: a 5 magnitude difference corresponds to a factor 100 in brightness (flux)

We have, therefore:

$$\frac{F_1}{F_2} = 100^{(m_2 - m_1)/5}$$

$$F_i = \frac{L_i}{4\pi d_i^2}$$

With F the flux, L the luminosity and d is the distance from us to the star. This is a *relative* scale.

Astronomers assign an ***absolute magnitude*** to a star, M, by determining what it's apparent magnitude would be *if* the star was located at 10 pc from Earth.

$$\frac{F_{10}}{F} = 100^{(m-M)/5} = \left(\frac{d}{10\ \mathrm{pc}}\right)^2$$

Or

$$M - m = 5 - 5\log_{10}(d)$$

Homework: With the previous definitions, show that a star's apparent magnitude, m, relative to the Sun, is related to the flux F received from the star by:

$$m = M_{\odot} - 2.5 \log_{10} \left( \frac{F}{F_{10,\odot}} \right)$$

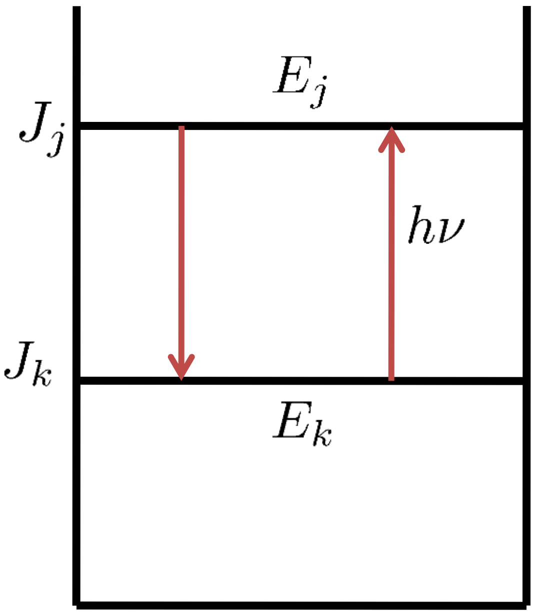
For a certain stellar class called Cepheid variable, the intrinsic luminosity L and absolute magnitude M can be determined theoretically, to high precision.

Since astronomers directly measure m, the above equation allows the distance to such a star to be determined. From this, astronomers build up the "Cosmological Distance Ladder", to measure ever greater distances.

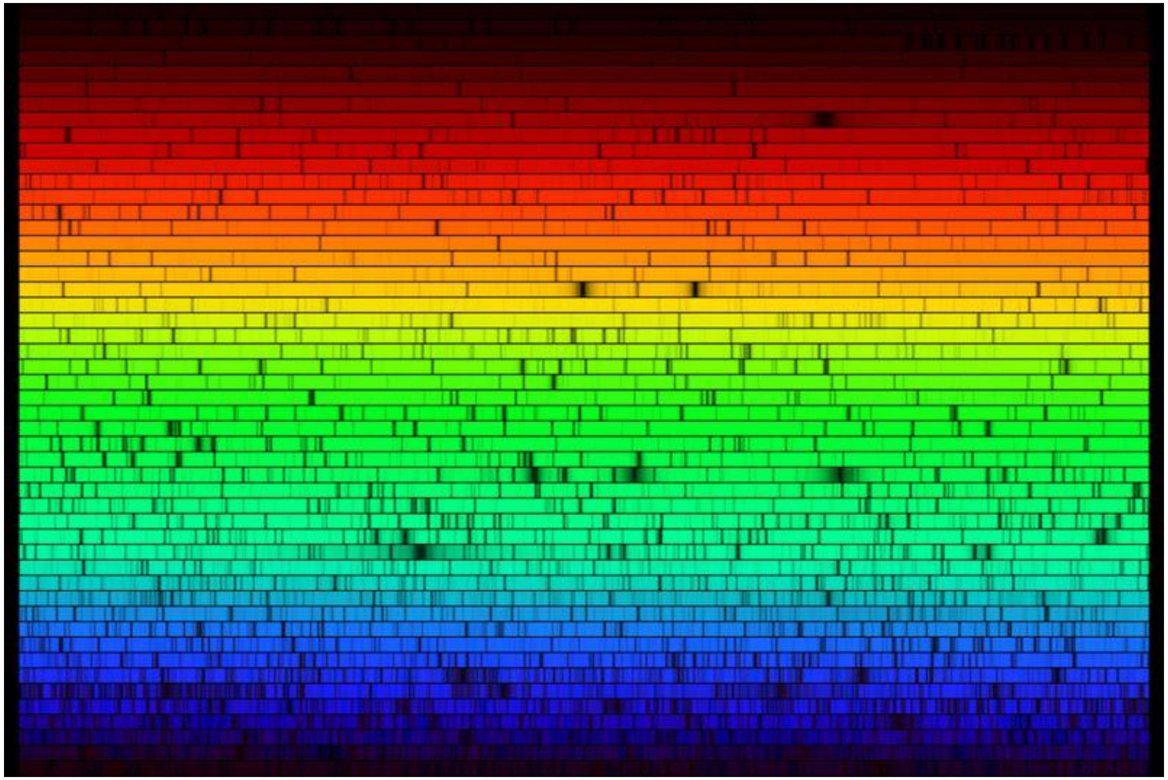
# Stellar Temperatures

- Astronomers measure the spectra of atomic transitions
- The spectral source is line *absorption* of continuum light in the stellar a*tmosphere*
- Photo-absorption and scattering can cause atomic transitions
- Population ratio between two atomic states in thermal equilibrium given by Boltzmann's formula:

$$\frac{n_j}{n_k} = \frac{g_i}{g_k} \exp\left(-\frac{E_j - E_k}{kT}\right)$$

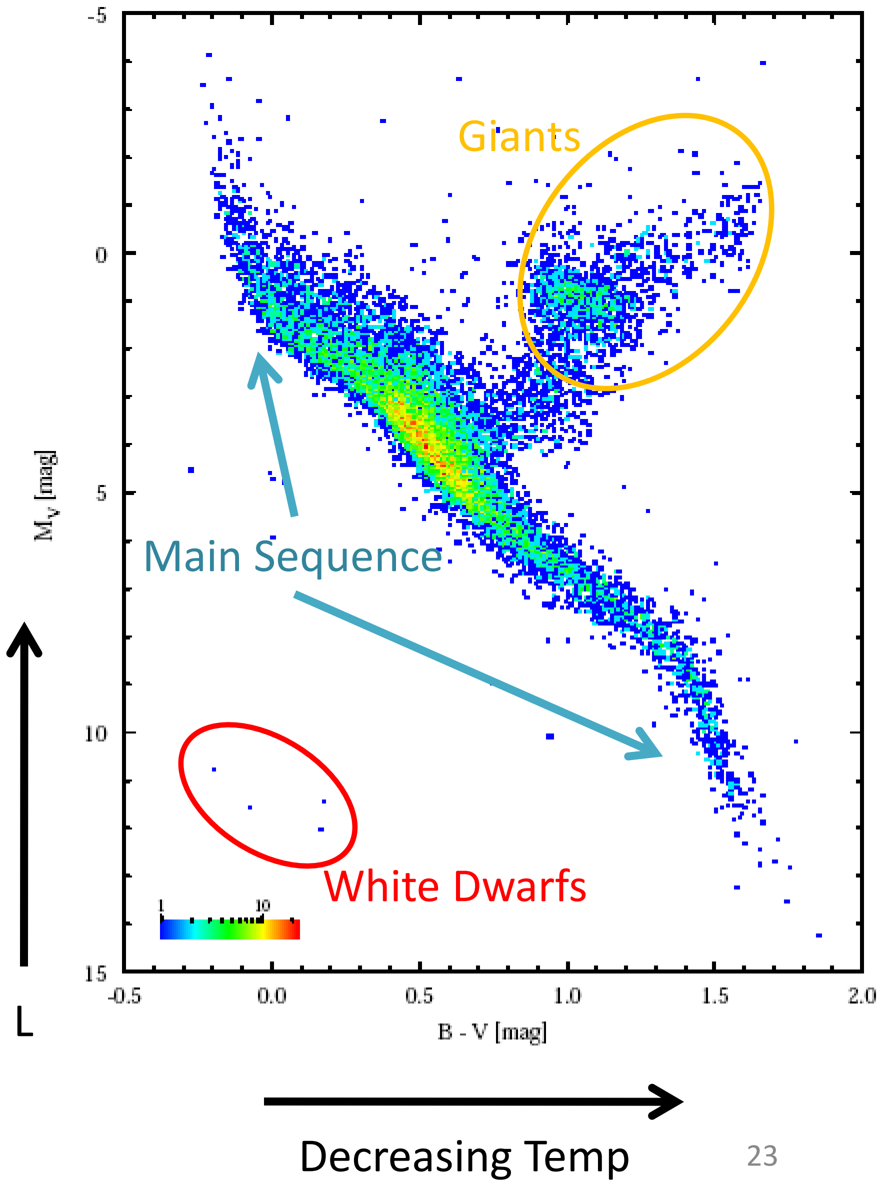


# A Stellar Visual Band Spectrum



# Hertzsprung-Russel Diagram

- Plot of absolute Magnitude against an "effective" temperature
- Intrinsic luminosity L from M
- Stephan-Boltzmann: $R_* = \frac{1}{T_e^2}\sqrt{\frac{L}{4\pi\sigma}}$
- If colour temperature of star (B-V) is known, a "quick" estimate of its Magnitude can be read off the H-R diagram!

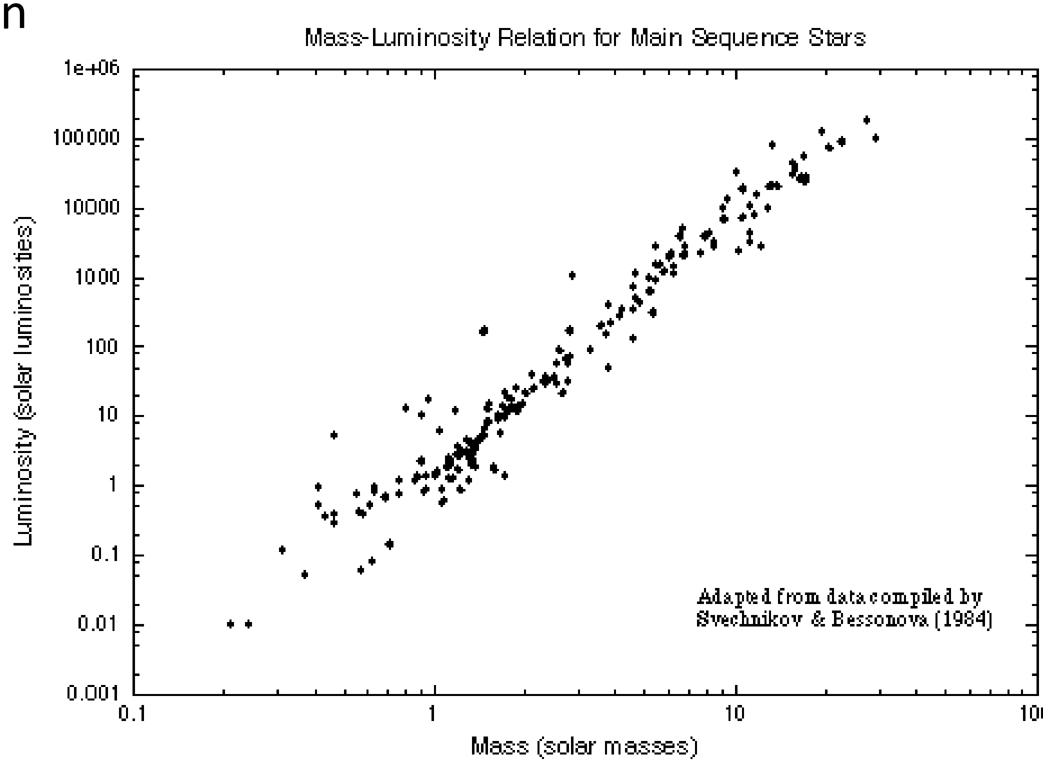


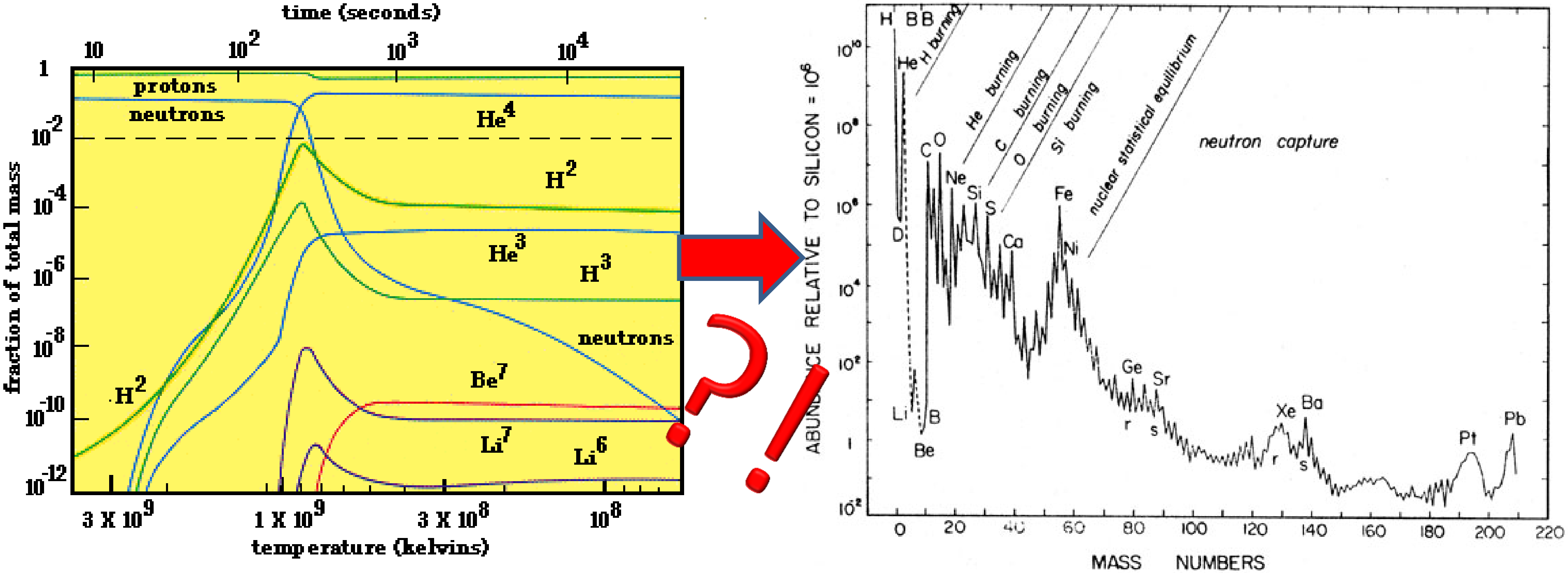
# Mass-Luminosity Relation

- Stellar masses only possible from eclipsing binary systems
- Relationship is a power law (Main Sequence):

$$L_* \propto M^a,\ 3 \leq a \leq 4$$

- We will see later in the course how this comes about






We are star-stuff. -- Carl Sagan

# NUCLEAR ASTROPHYSICS

# Primordiale Nukleosynthese

$$^2H: \quad n + p \rightarrow d + \gamma$$

$$^3He: \quad d + p \rightarrow {}^3He + \gamma$$

$$d + d \rightarrow {}^3He + n$$

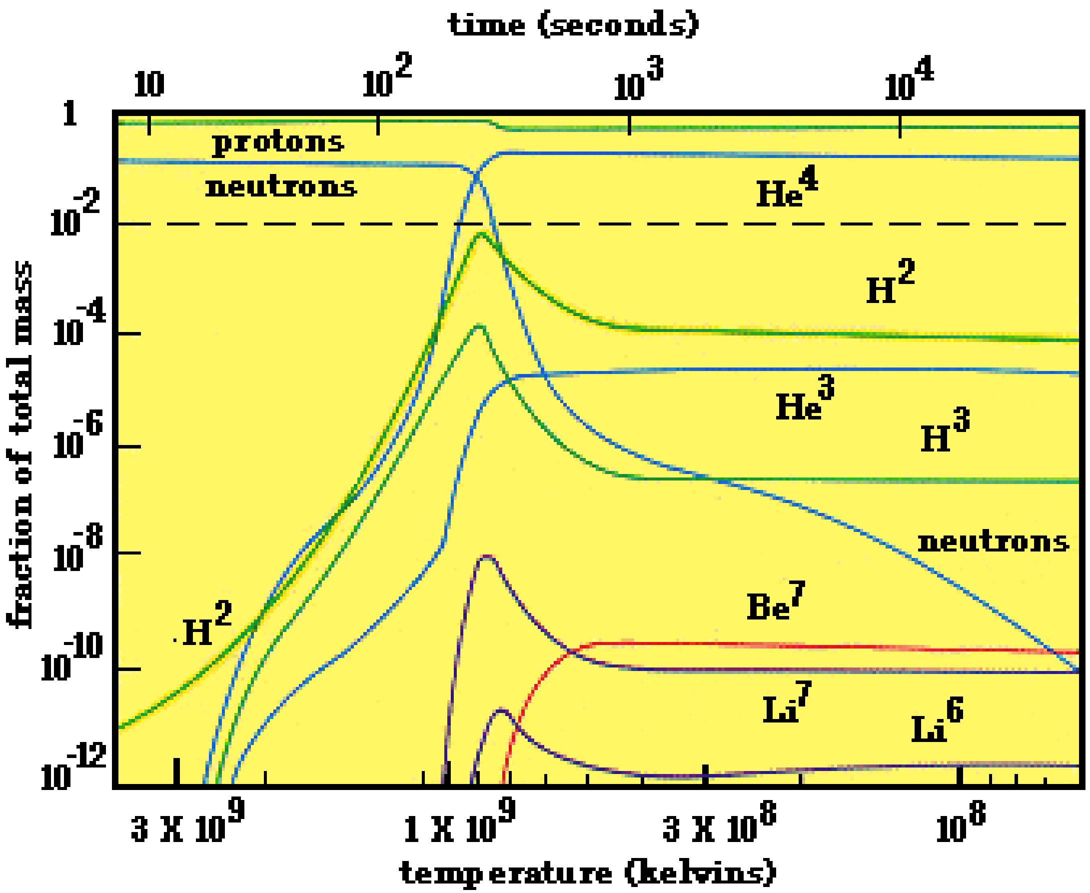
$$^4He: \quad {}^3H + p \rightarrow {}^4He + \gamma$$

$${}^3He + n \rightarrow {}^4He + \gamma$$

$$^4He + {}^3H \rightarrow {}^7Li + \gamma$$

$$^4He + {}^3He \rightarrow {}^7Be + \gamma$$

$$d + {}^4He \rightarrow {}^6Li + \gamma$$



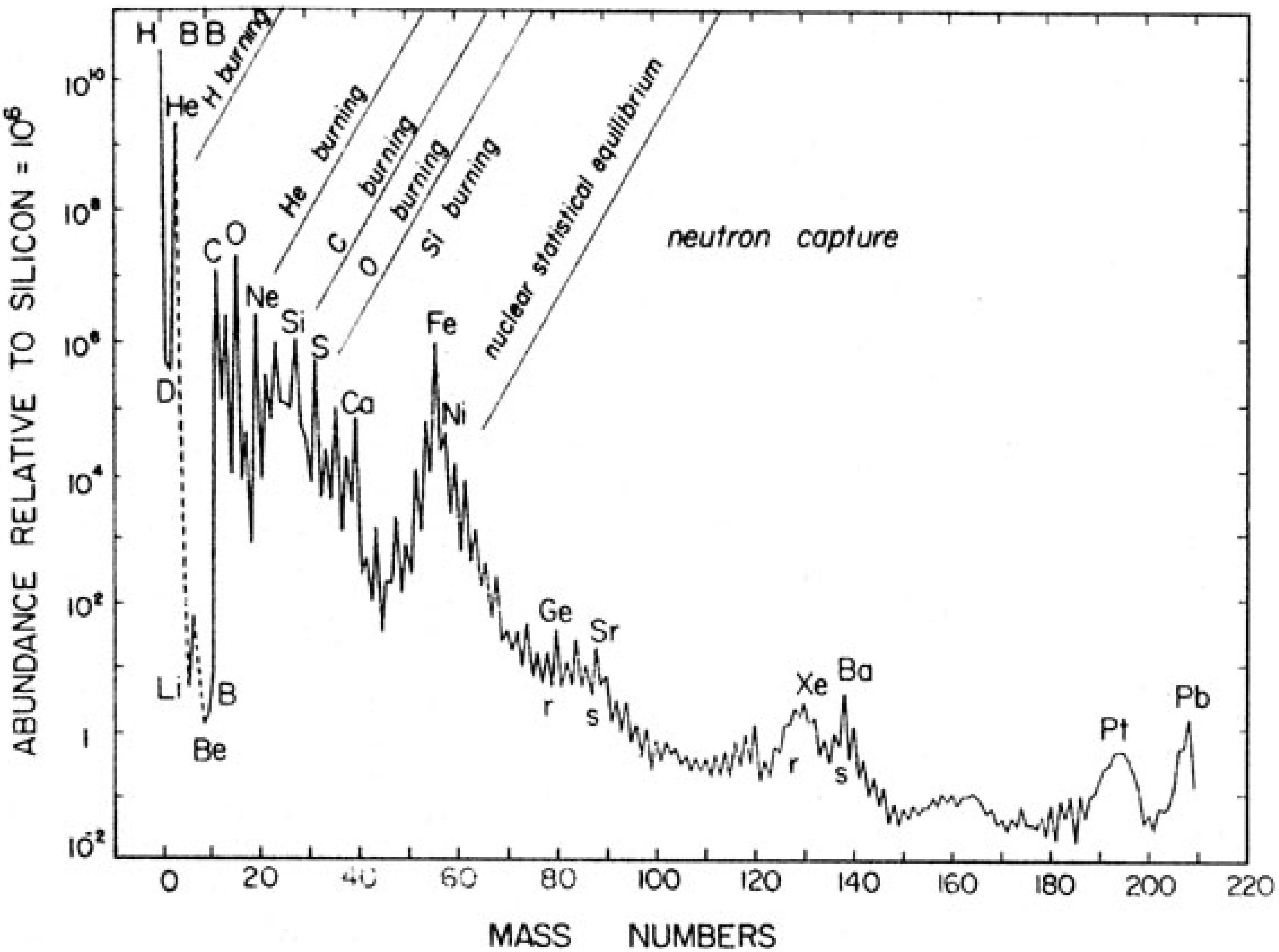

E. Wright, Berkeley

Keine Fusion zu schwereren Elementen, da es keinen stabilen Kern mit A=5 und A=8 gibt

$$p : {}^4He : d : {}^3He = 77 : 23 : 10^{-4} : 10^{-4}$$

Nur < 0.1% „Metalle“

# Solar Abundances



# Nuclear Astrophysics Essentials

- How did the Primordial Abundances change?
- What nuclear processes are responsible for chemical enrichment? (Nucleosynthesis)
- *Where* in the Universe do these nuclear processes take place? (Astrophysical Site)
  - Astronomy, space missions, meteorites
  - Theoretical modelling
  - Nuclear Physics
- What nuclear physics quantities are important?
  - Astronomical observations
  - Nuclear physics experiments

# Best Known Star: Sun

- Mean distance from Earth:
  $1.496 \times 10^8$ km = 1 AU

- Mass:
  $2 \times 10^{30}$ kg

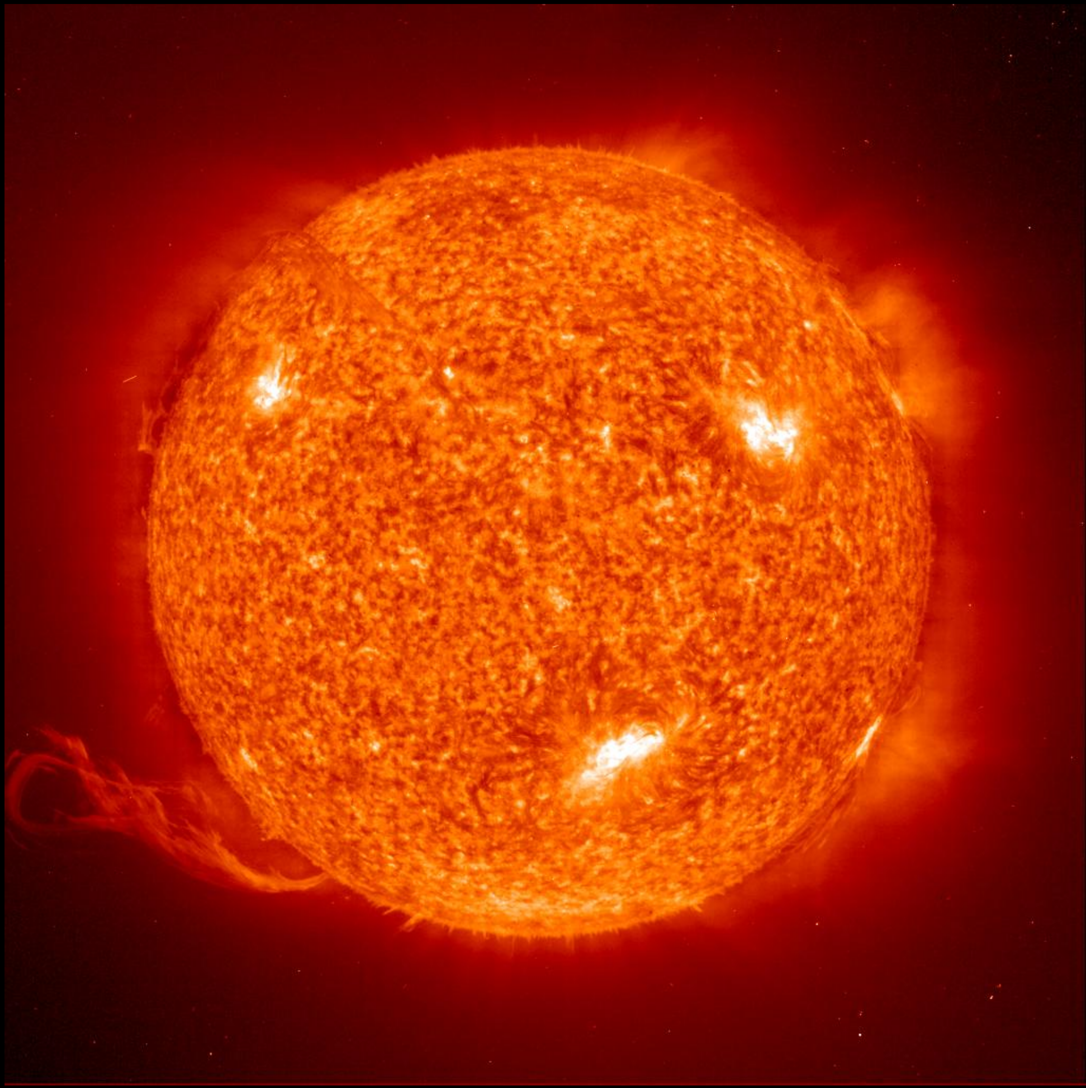
- Radius:
  700 000 km

- mean density:
  1,41 g/cm$^3$

-Luminosity:
  3.826 x 10

- Core Temperature:
  ~ 15 MK

- Age: 4,6 Gyr



# Proton-Proton-Chain

$p + p \rightarrow d + e^+ + \nu$

$p + d \rightarrow {}^3He + \gamma$

86% | 14%

$^3He + {}^3He \rightarrow {}^4He + 2p$

**PP-I**

$Q_{eff}$= 26.20 MeV

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

99.7% | 0.3%

$^7Be + e^- \rightarrow {}^7Li + \nu$

$^7Li + p \rightarrow 2\ {}^4He$

**PP-II**

$Q_{eff}$= 25.66 MeV

$^7Be + p \rightarrow {}^8B + \gamma$

$^8B \rightarrow {}^8Be + e^+ + \nu$

↓

$2\ {}^4He$

**PP-III**

$Q_{eff}$= 19.17 MeV

*Netto:* $4p \rightarrow {}^4He + 2e^+ + 2\nu + Q_{eff}$

# Binding Energy per Nucleon

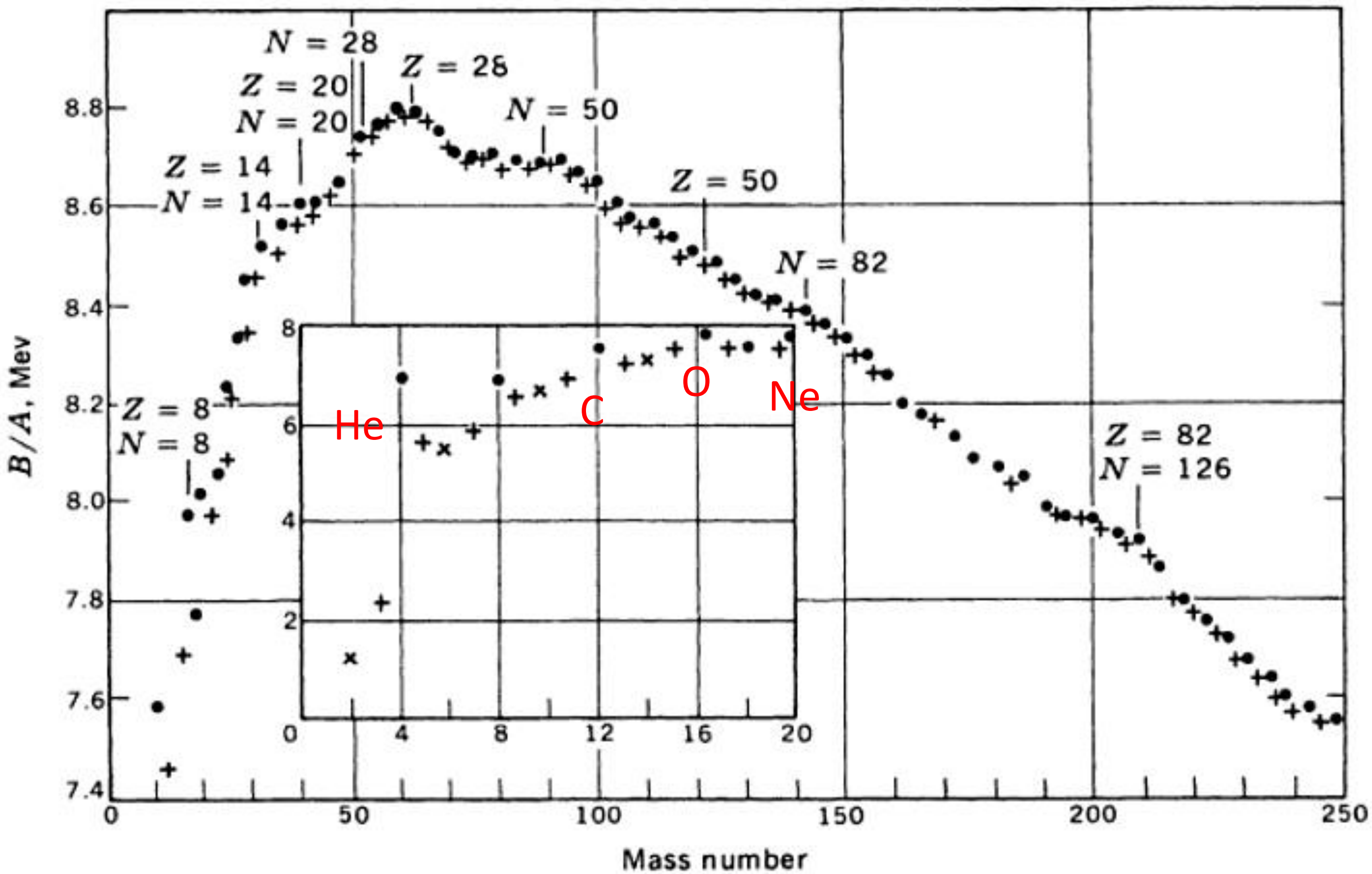
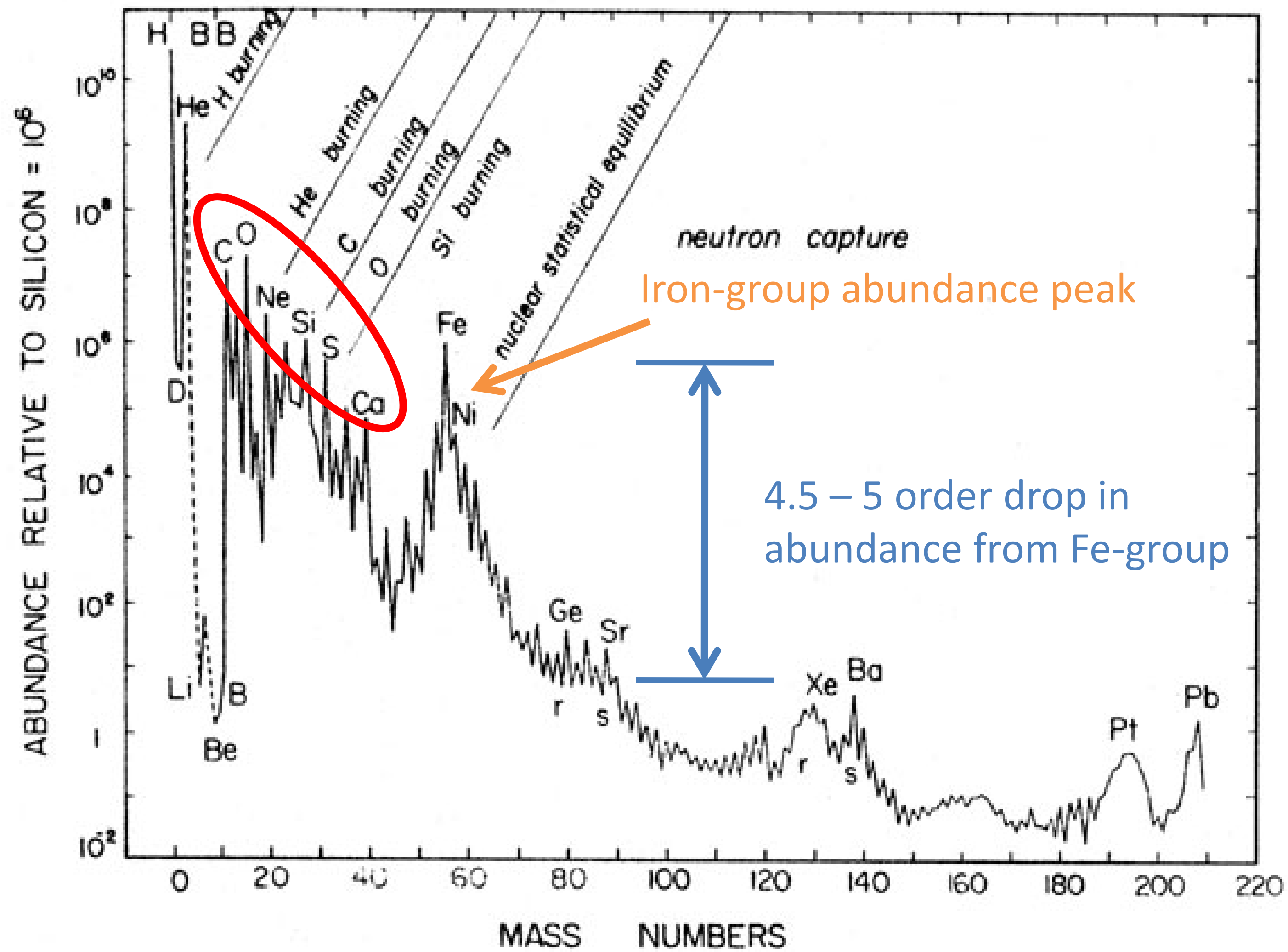



**Fig. 7-1** The binding energy per nucleon of the most stable isobar of atomic weight $A$. The

If reaction products have larger binding energy than reactants, reaction is exothermic and releases energy (heat)

# Solar Abundances Continued



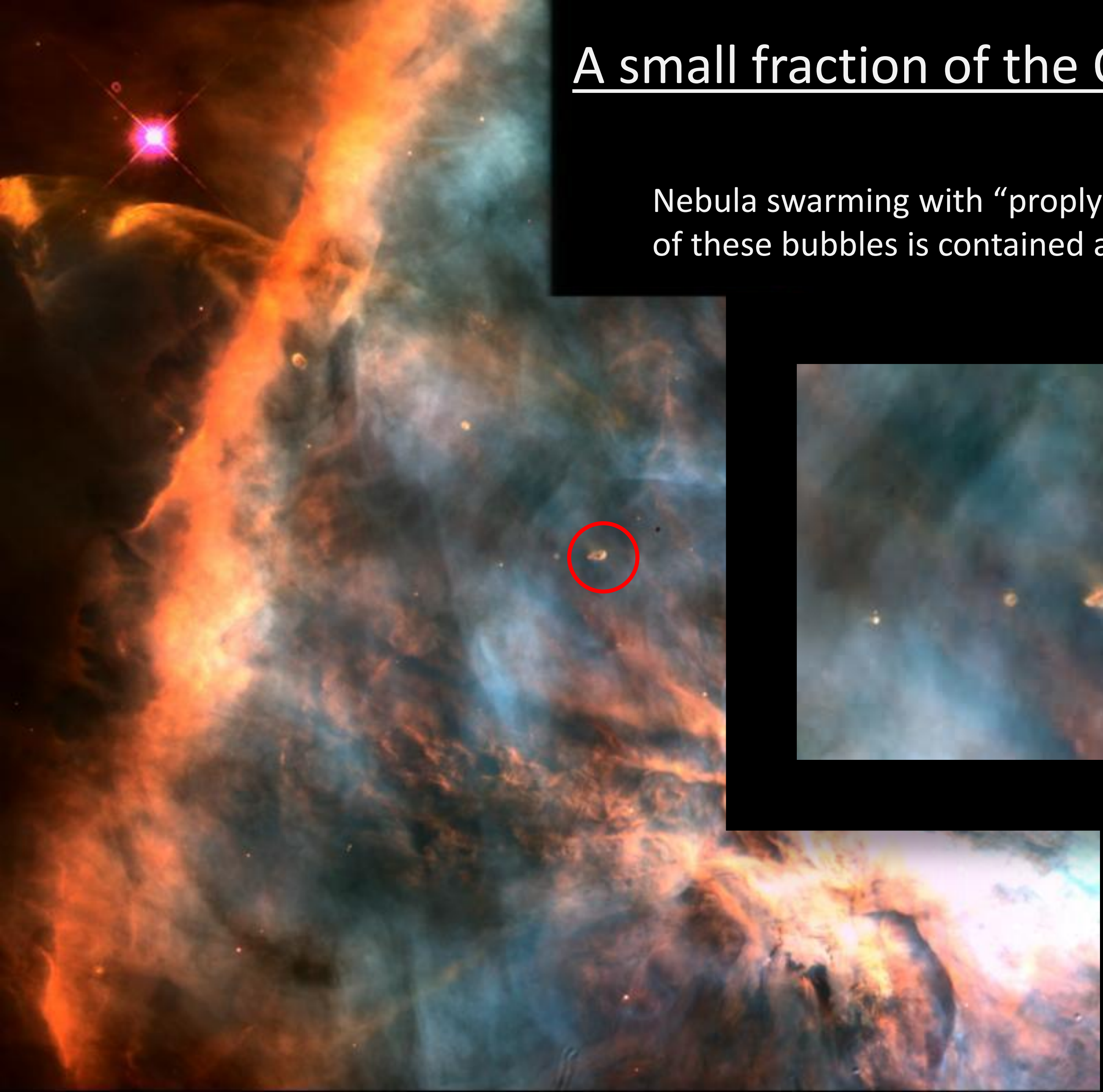

$\alpha$-particle nuclei have local maxima relative to neighbouring masses

- Will learn more about this further into the course

Young Stellar Objects (YSO)

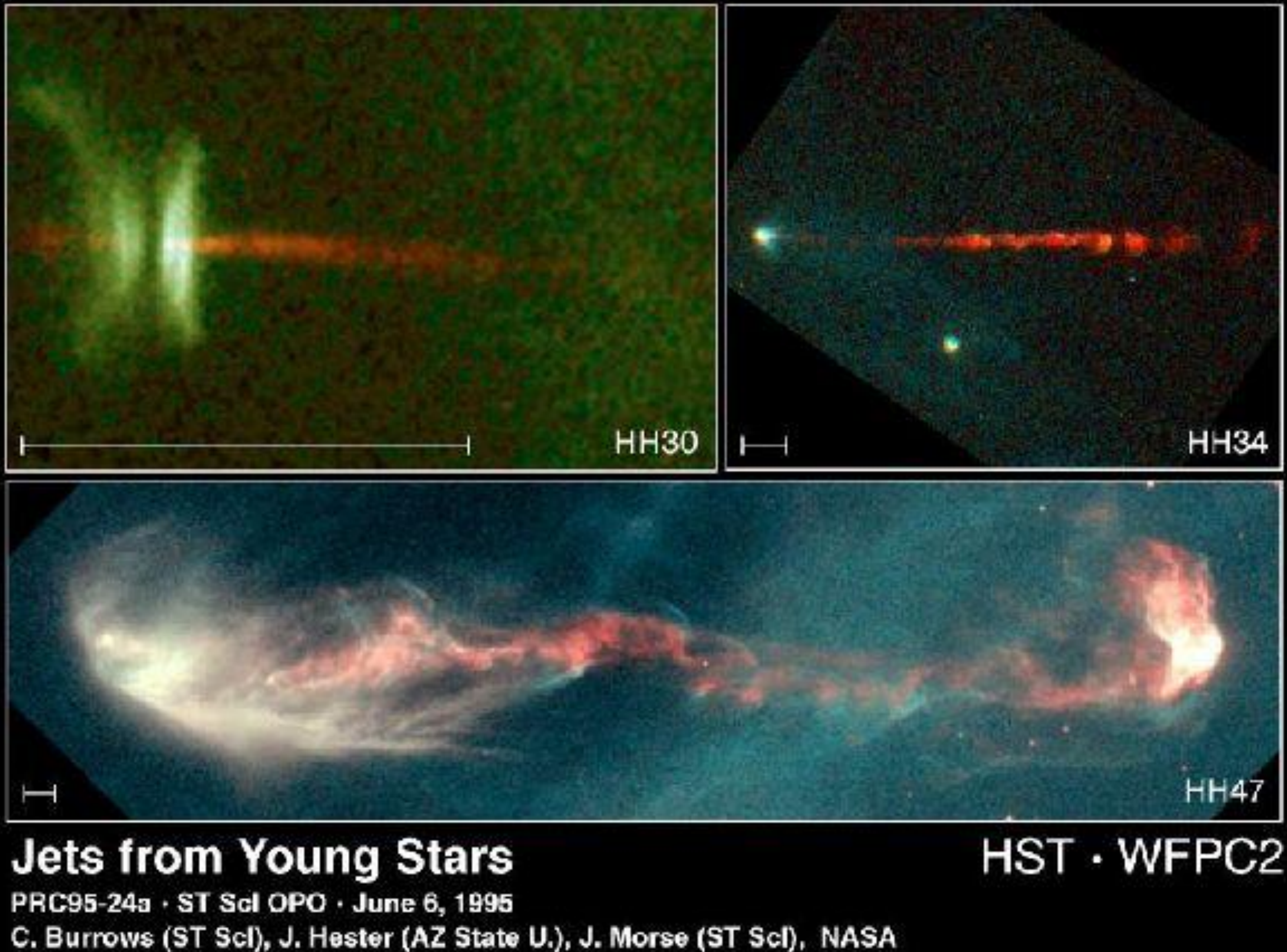
# WHAT SITES DO WE KNOW ABOUT?

# A small fraction of the Orion Nebula

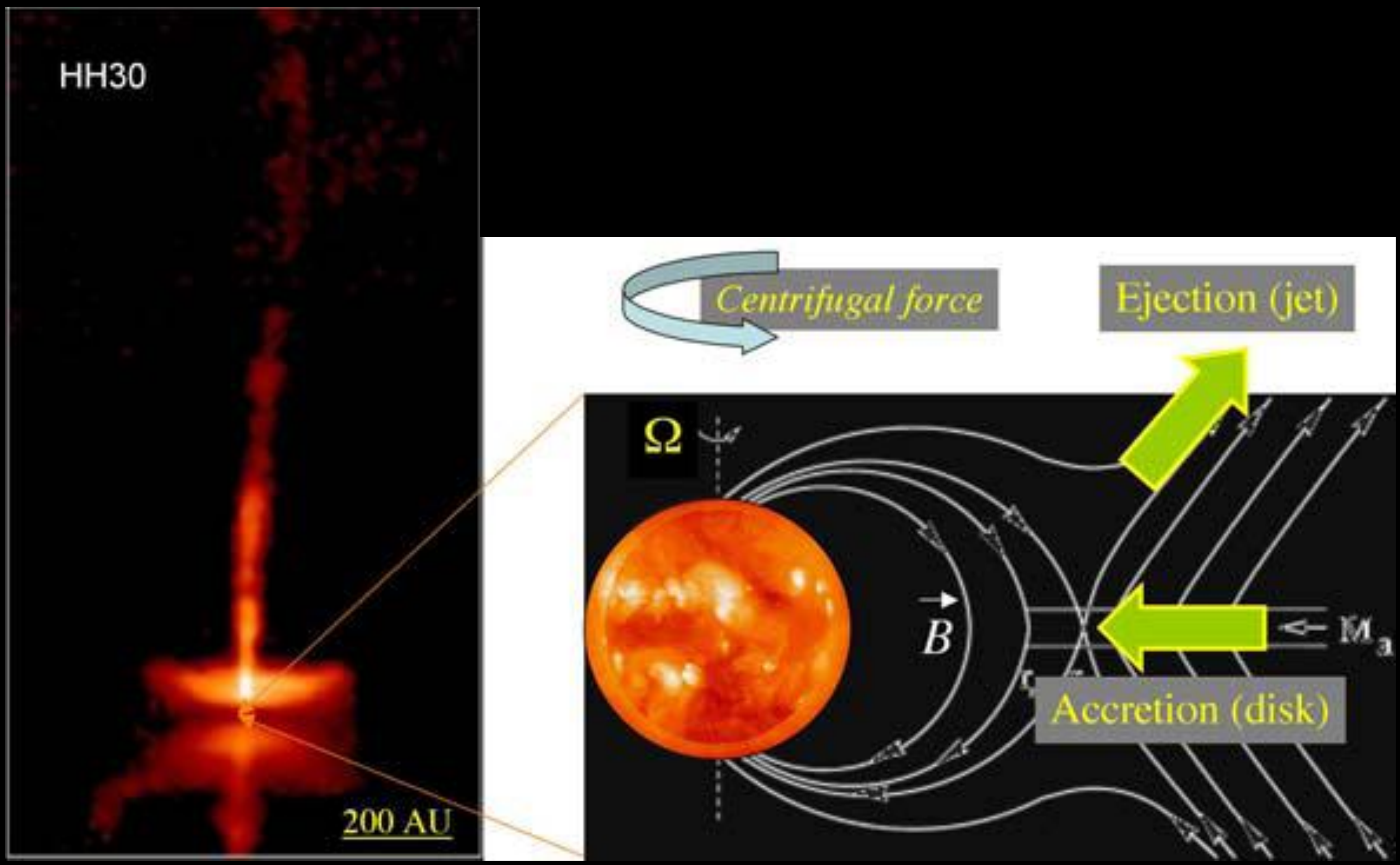


Nebula swarming with "proplyds". Within each of these bubbles is contained a new protostar

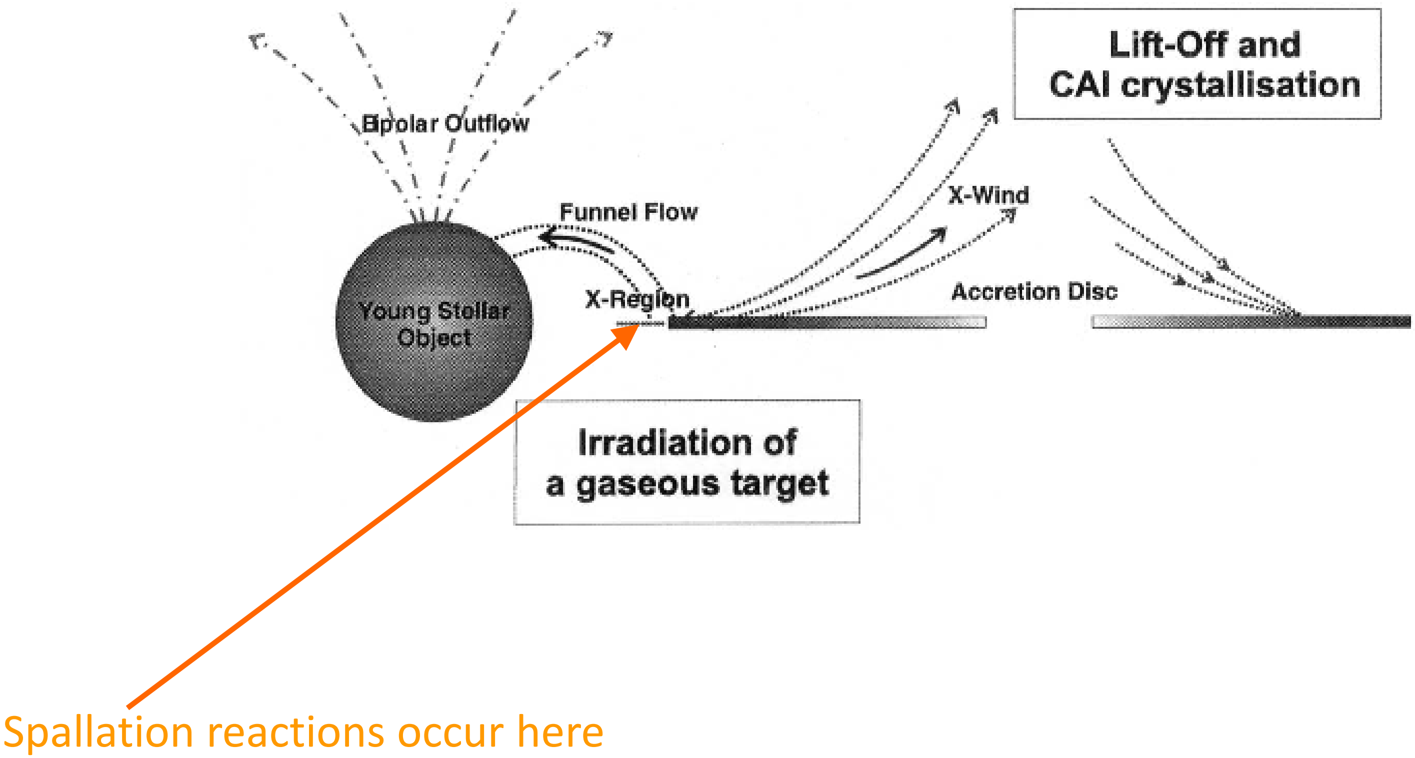
# An Enigma: T Tauri Stars



# Irradiation Environment

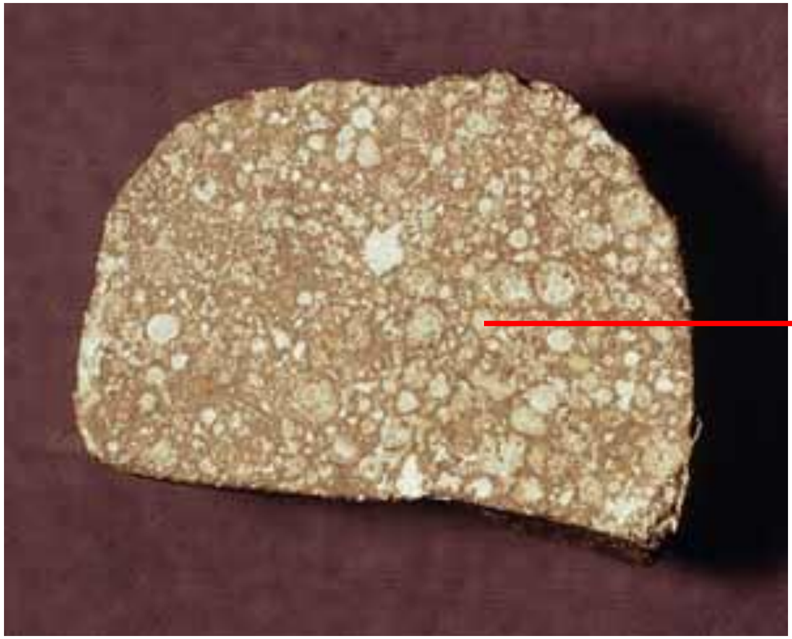


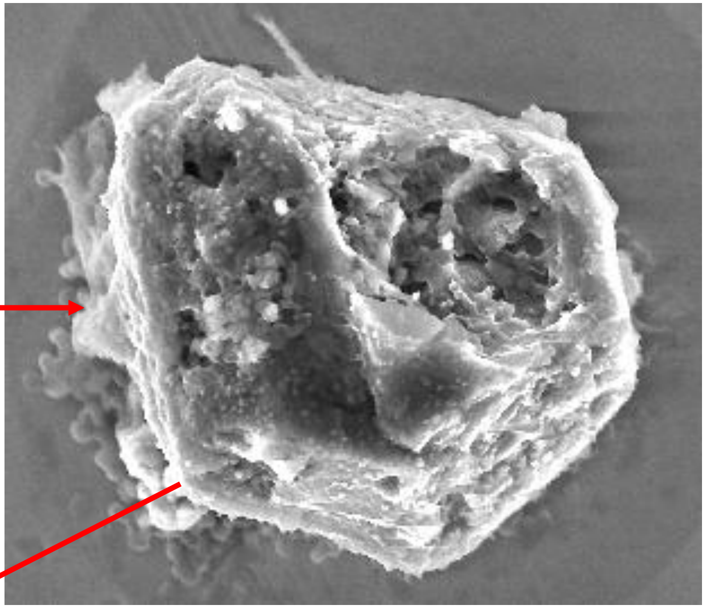
# **The Internal** Irradiation **Source**




- Flare events from young Sun accelerate light particles to 10's of MeV
- Spallation reactions (p,X), ($^3$He,X), ($\alpha$,X) produce radioisotopes
- X-ray winds disperse the gas and condensates out of production zone

# Messengers of the Stars





Allende Meterorite

SiC Grain (0.1—20) microns

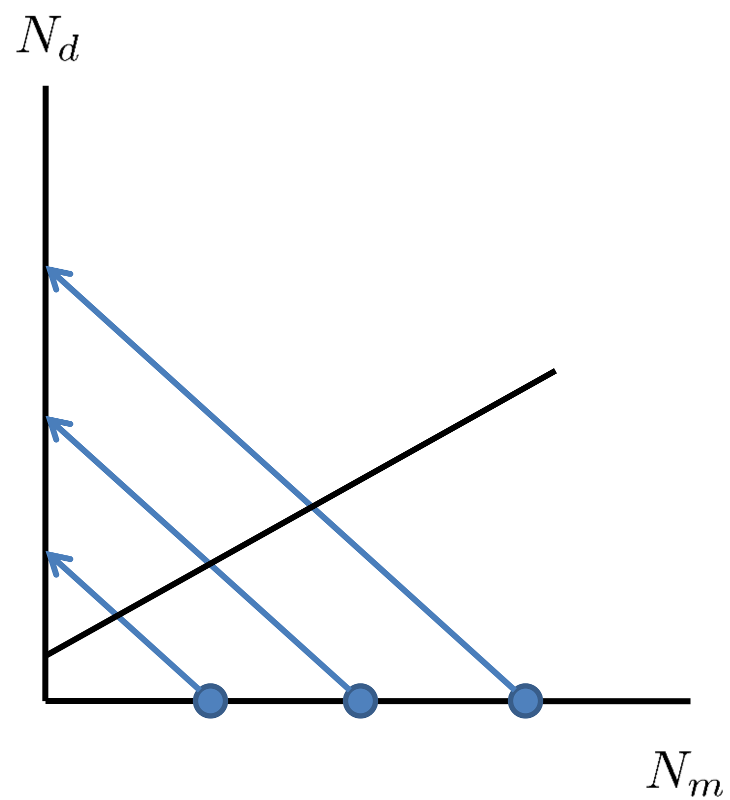
Measurements of isotopic abundances provides a measure
of the nucleosynthesis at the site of origin → model constraints

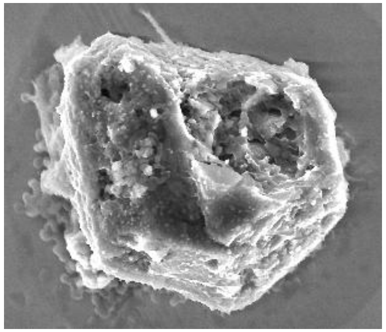
# What is an Isochrone, You Ask?

$$N_m = N_0 \exp(-\lambda t)$$

$$N_d = N_{init} + N_0[1 - \exp(-\lambda t)]$$

$$\frac{dN_d}{dt} \Big/ \frac{dN_m}{dt} = \frac{dN_d}{dN_m} = -1$$



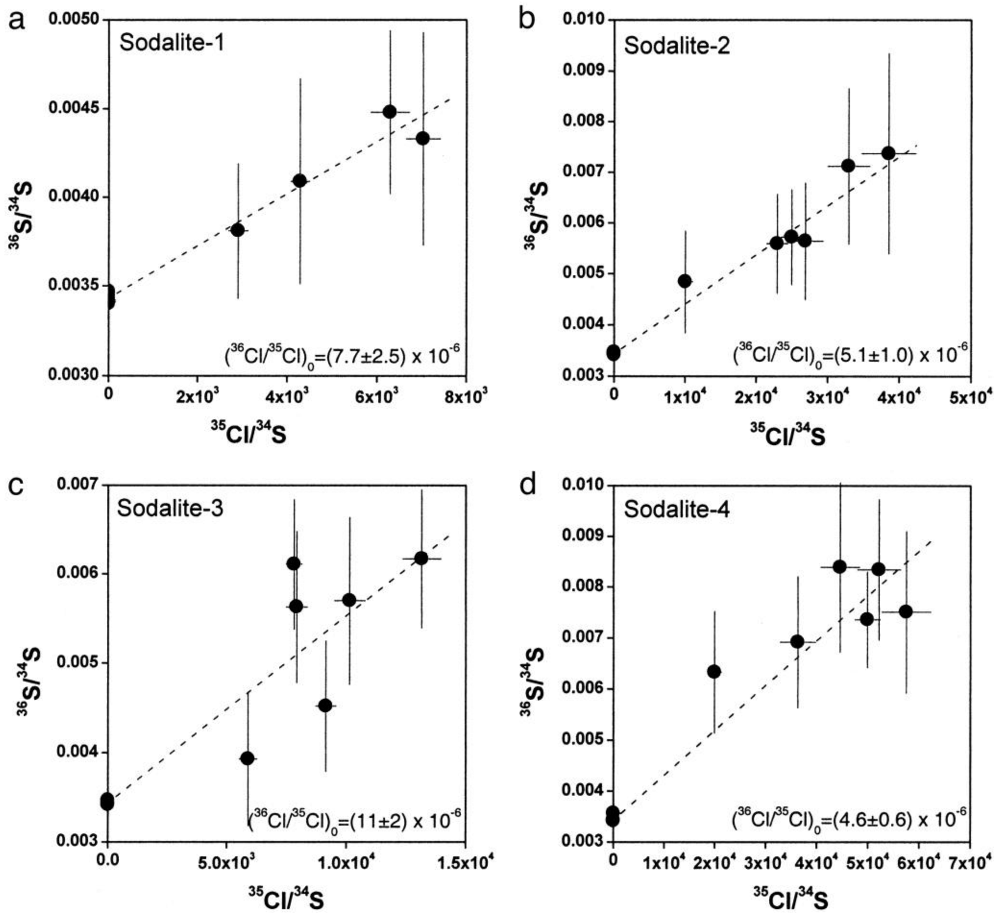
# Radioisotopes Discovered in the Early Solar System

A mystery: how is this possible!

| Radioisotope | $t_{1/2}$ |
|---|---|
| $^{7}Be$ | 53 days |
| $^{10}Be$ | 1.5 My |
| $^{36}Cl$ | 0.3 My |
| $^{41}Ca$ | 0.1 My |
| $^{53}Mn$ | 3.7 My |
| $^{60}Fe$ | 1.5 My |
| $^{63}Ni$ | 100 y |
| $^{92}Nb$ | 36 My |
| $^{91}Nb$ | 680 y |

# Recent Discovery of $^{36}Cl$

- Original amount of $^{36}Cl$ in inclusion can be inferred by intercept
- From slopes: $(^{36}Cl/^{35}Cl)_o = 5 \times 10^{-6}$
- Condensation time ~ 1.5 My → original $^{36}Cl/^{35}Cl)_o = 1.6 \times 10^{-4}$
- No AGB model can yield this much $^{36}Cl$
  - internal source component

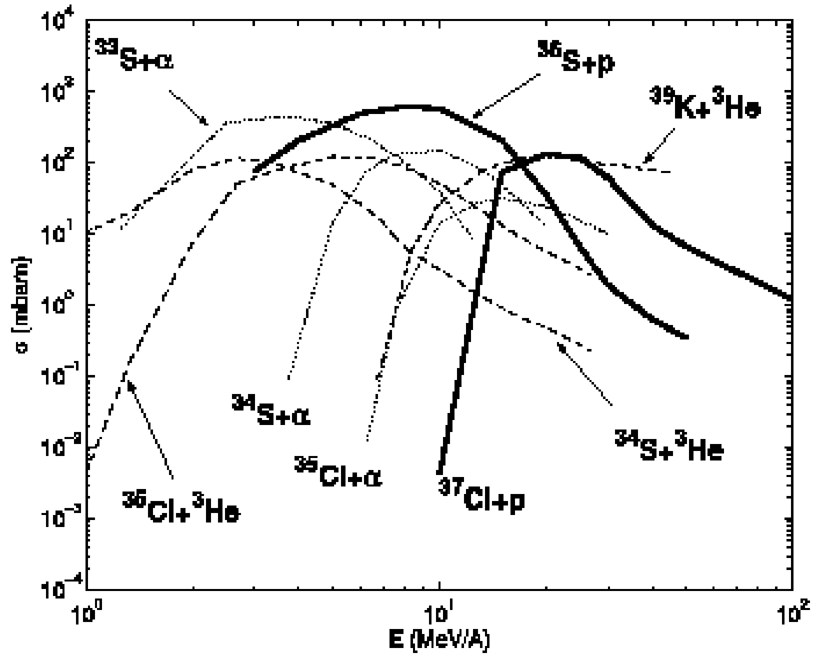



Y. Lin et al., PNAS 102 (2005)

# $^{36}$Cl Production Cross Sections

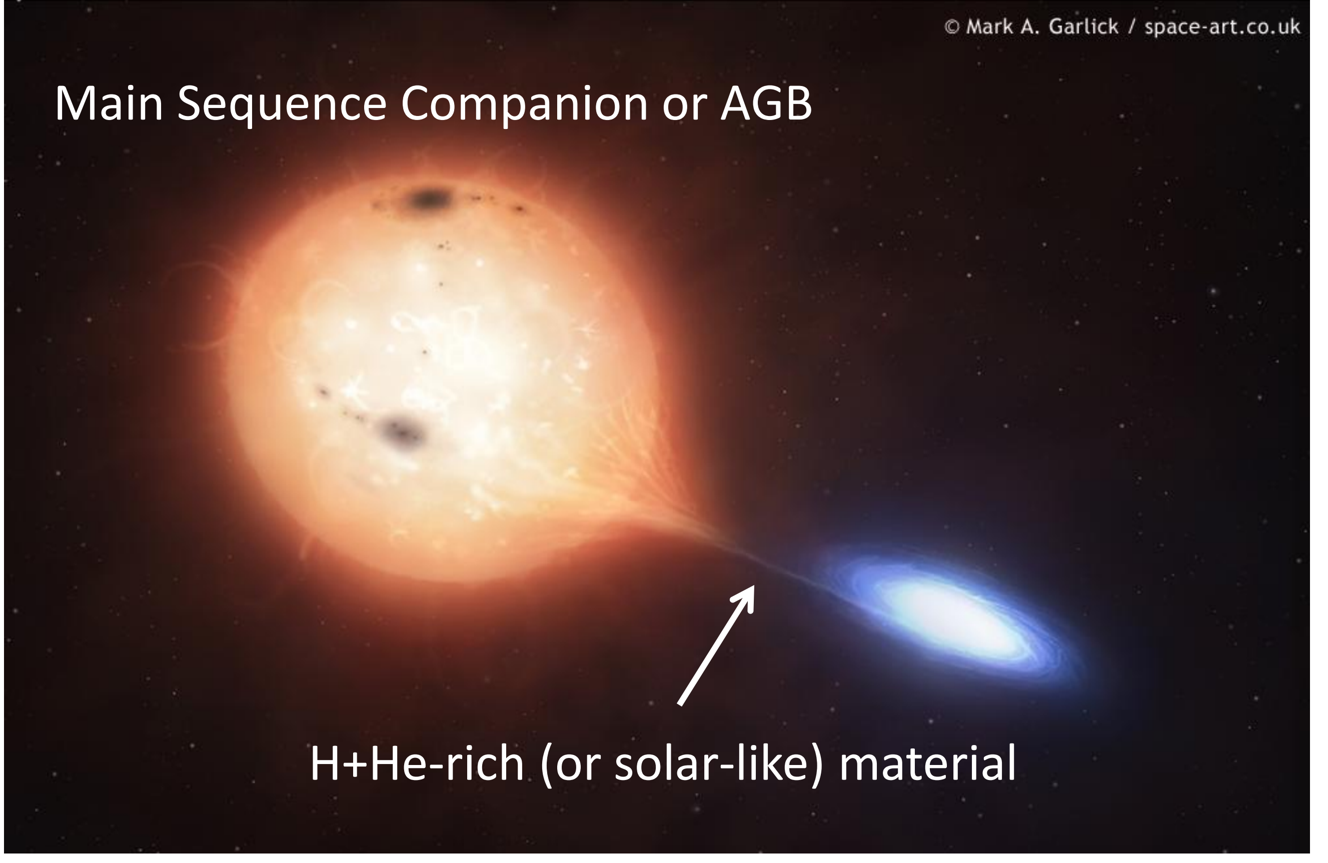
- Spallation reactions all unmeasured for $^{36}$Cl production in ESS
- Relevant energy range from 1-few 10's of MeV
- Some of these are nicely in the domain of MLL tandem

M. Gounelle et al., ApJ 640 (2005)




**Some Reactions:**

$^{33}$S($\alpha$,X), $^{34}$S($^{3}$He,X), $^{34}$S($\alpha$,X), $^{36}$S(p,X), $^{35}$Cl($^{3}$He,X),$^{35}$Cl($\alpha$,X), $^{37}$Cl(p,X), $^{39}$K($^{3}$He,X)

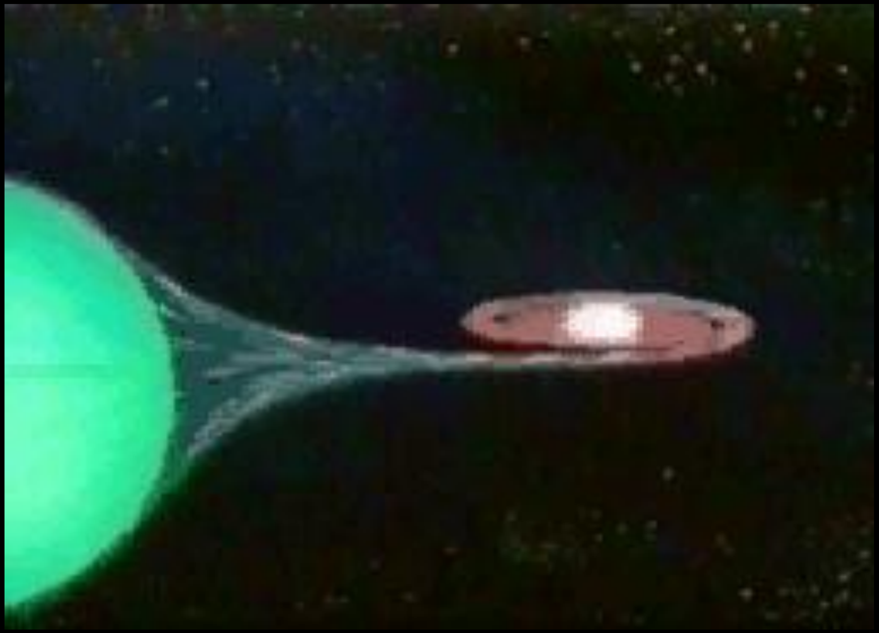



Cataclysmic Variables

# WHAT SITES DO WE KNOW ABOUT?

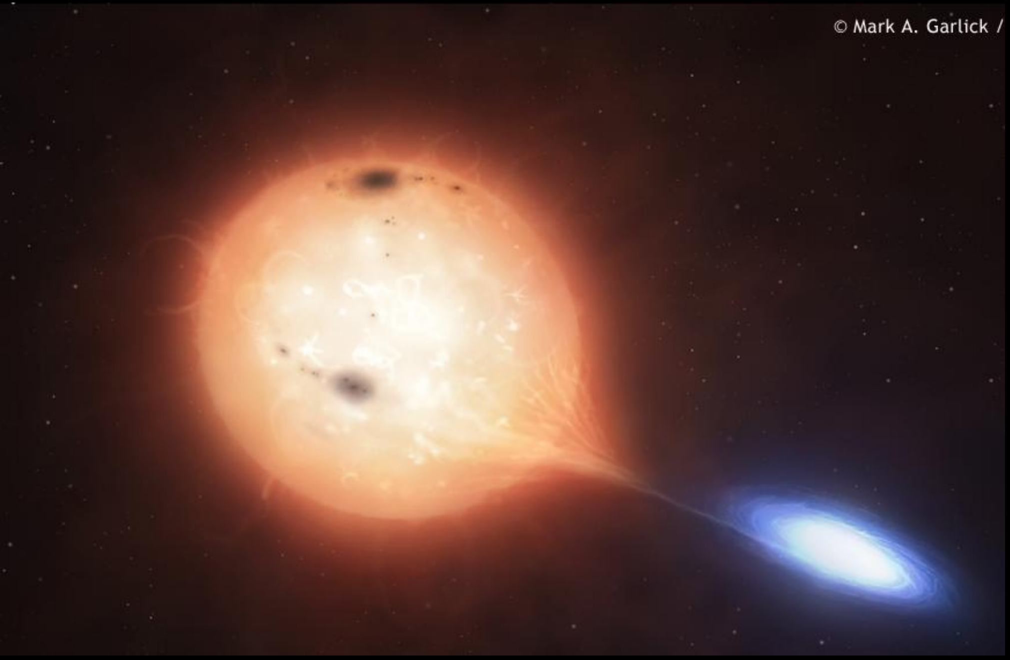
# Binary CV

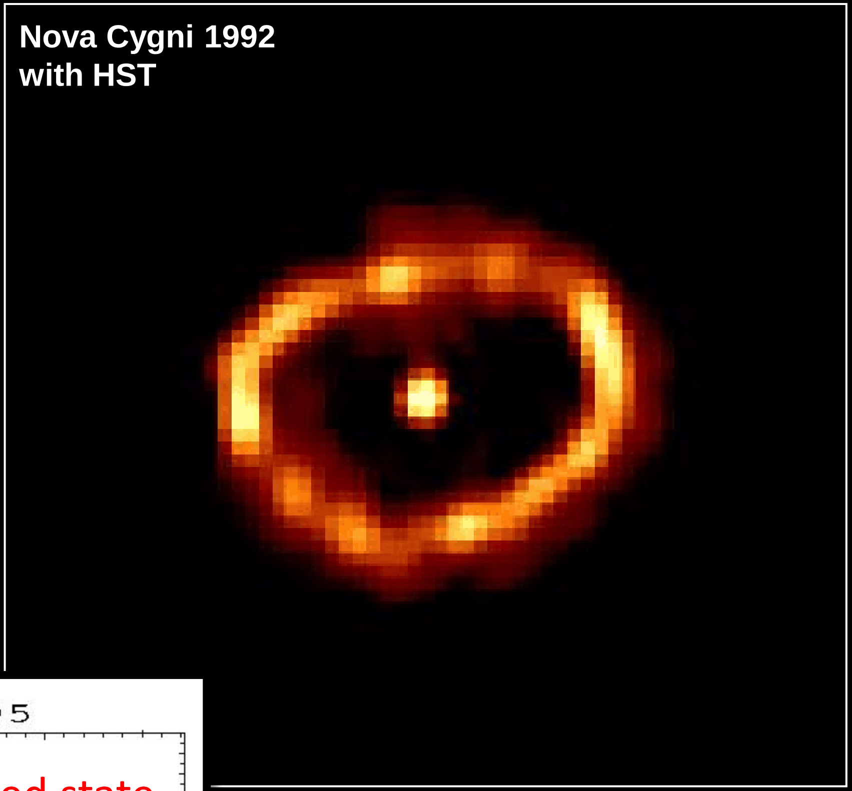
| | Nova | X-Ray Burst |
|---|---|---|
| $T_{max}$ | 400 MK | 2 GK |
| $\rho_{max}$ | $10^5$ g/cm$^3$ | $10^6$ g/cm$^3$ |
| Ejecta | yes | ? |

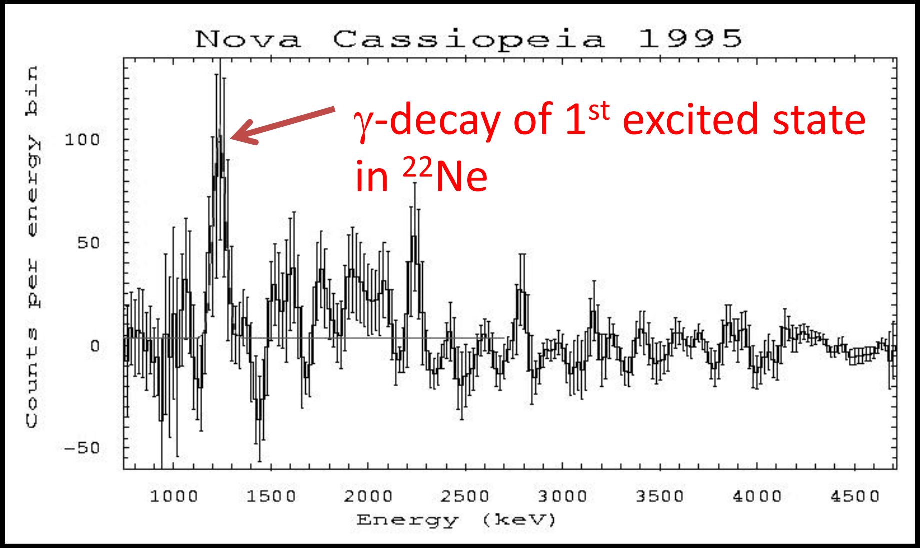


Note: It is still an area of active theoretical and observational work to determine if any material is able to escape the gravitational well of the neutron star.

# Novae Explosions




Courtesy Anatoli Iyudin

# Nova Explosions

- Ejecta abundances are sensitive to $(p,\gamma)$ reaction rates
- It is these rates that we must measure in the nuclear physics lab
- This will be a topic of future lecture

Cosmic Explosions:  From Stellar Death Comes Life

# SUPERNOVAE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Something to think about.....

Sun's Luminosity: $3.826 \times 10^{33}$ erg/s
Age of Sun: about $4 \times 10^{9}$ yr

Order of magnitude luminous energy output of SN: $10^{50}$ erg

Determine how much luminous energy Sun has emitted to date.

Compare this to SN luminous output.

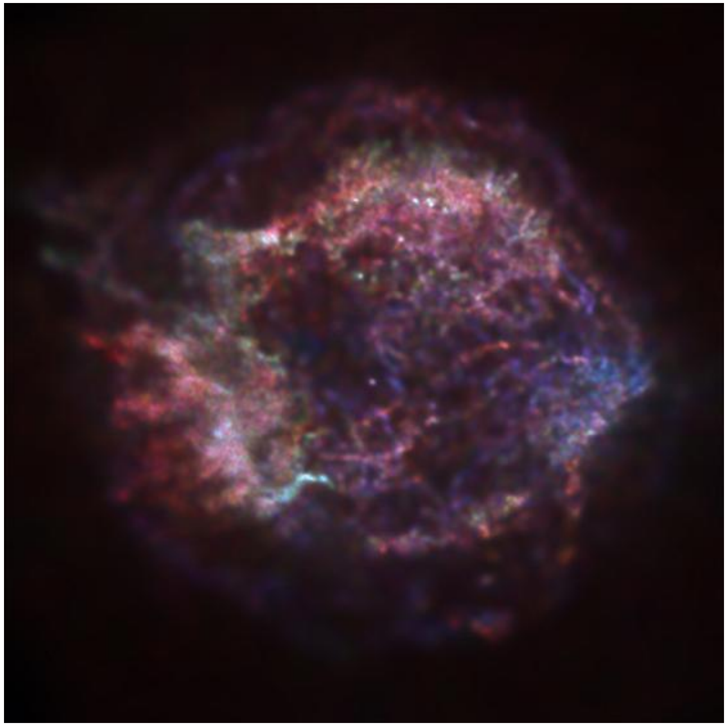
Then:

SN luminous lightcurve lasts for ~ 2 weeks. In that time, $10^{50}$ erg of energy is radiated away.

How many stars similar to our Sun would be required to radiate the same amount of energy in 2 weeks?

Once you have that number, ask yourself how many stars there are in a typical galaxy.

# Supernovae



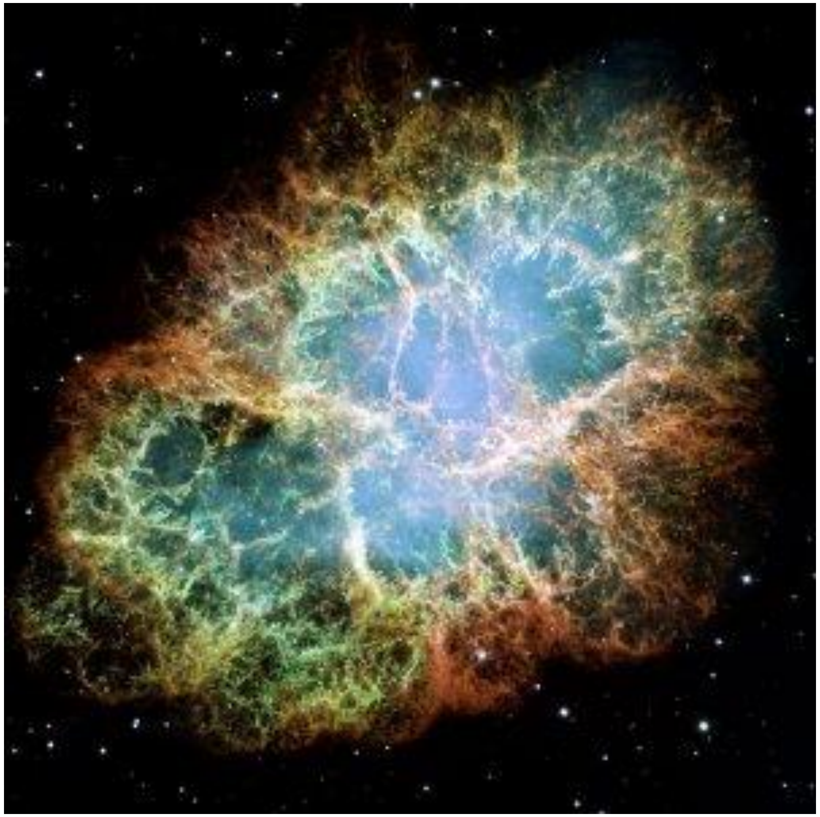
Animation: NASA/CXC/A.Hobart

# Super Nova Explosions

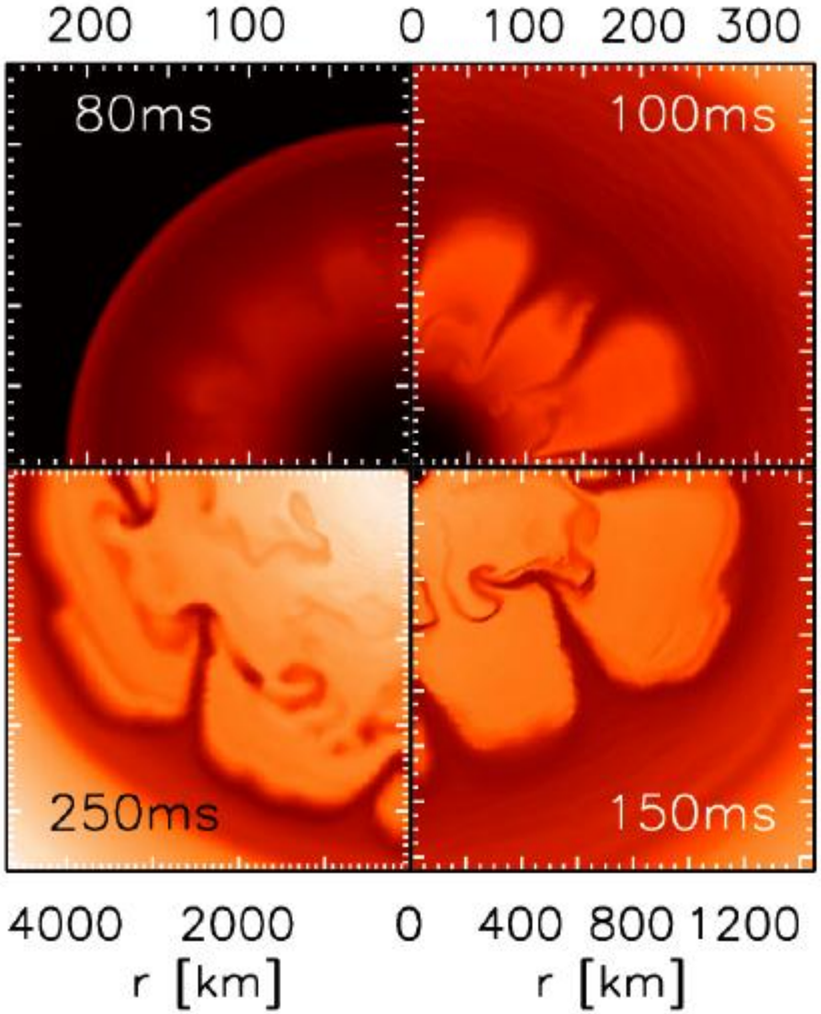
- Ejecta abundances are sensitive to only a few (p,$\gamma$) reaction rates
- Other abundances are sensitive to nuclear *masses*
- Why this is so will be a topic of future lecture

# How do stars explode?

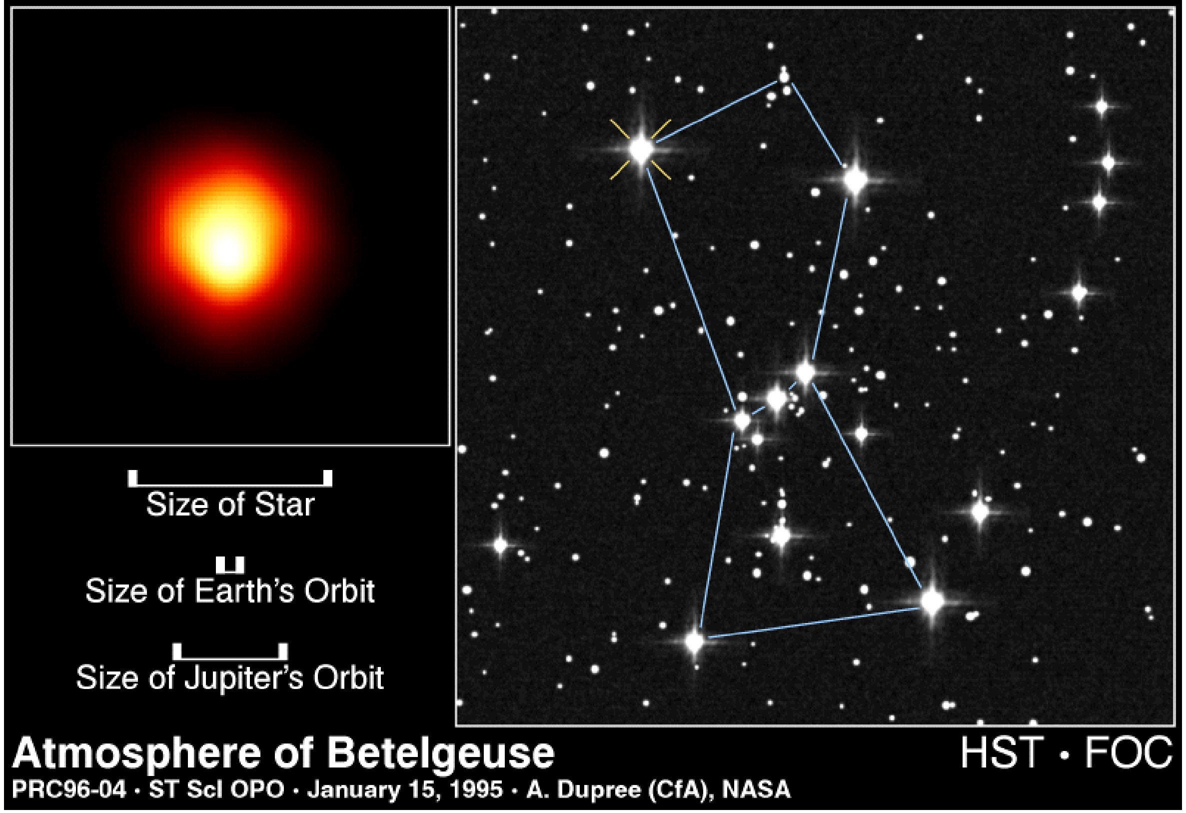
Example: delayed neutrino-driven Explosion of ONeMg Cores



Crab Nebula




F.S. Kitaura, H.-Th. Janka, W. Hillebrandt, Astron. Astrophys. 450 (2006) 345.




"Real time" nucleosynthesis right before your very eyes! $^{13}C(\alpha,n)^{16}O$

# IN SITU NUCLEOSYNTHESIS

# *In Situ* Nucleosynthesis

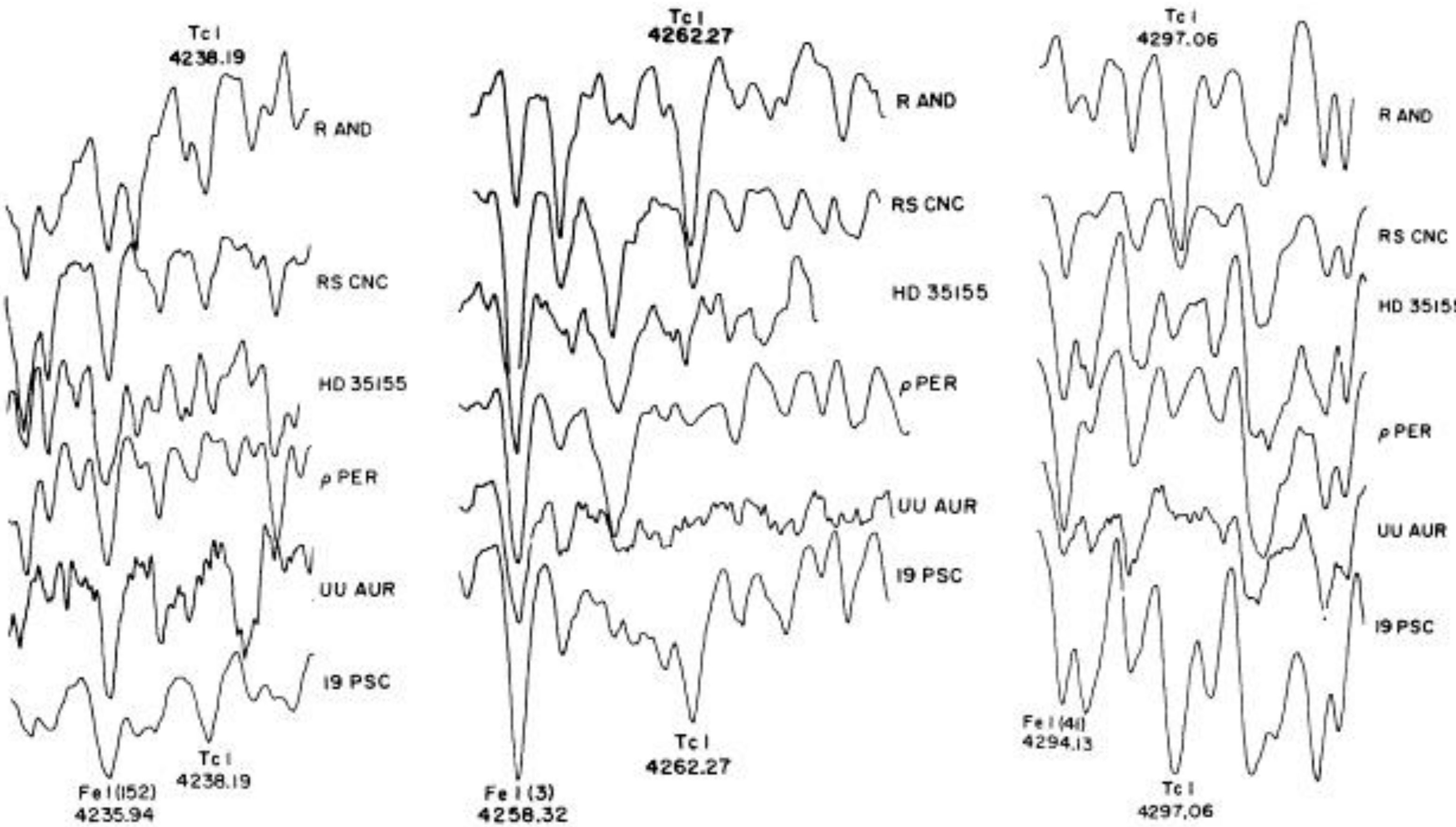
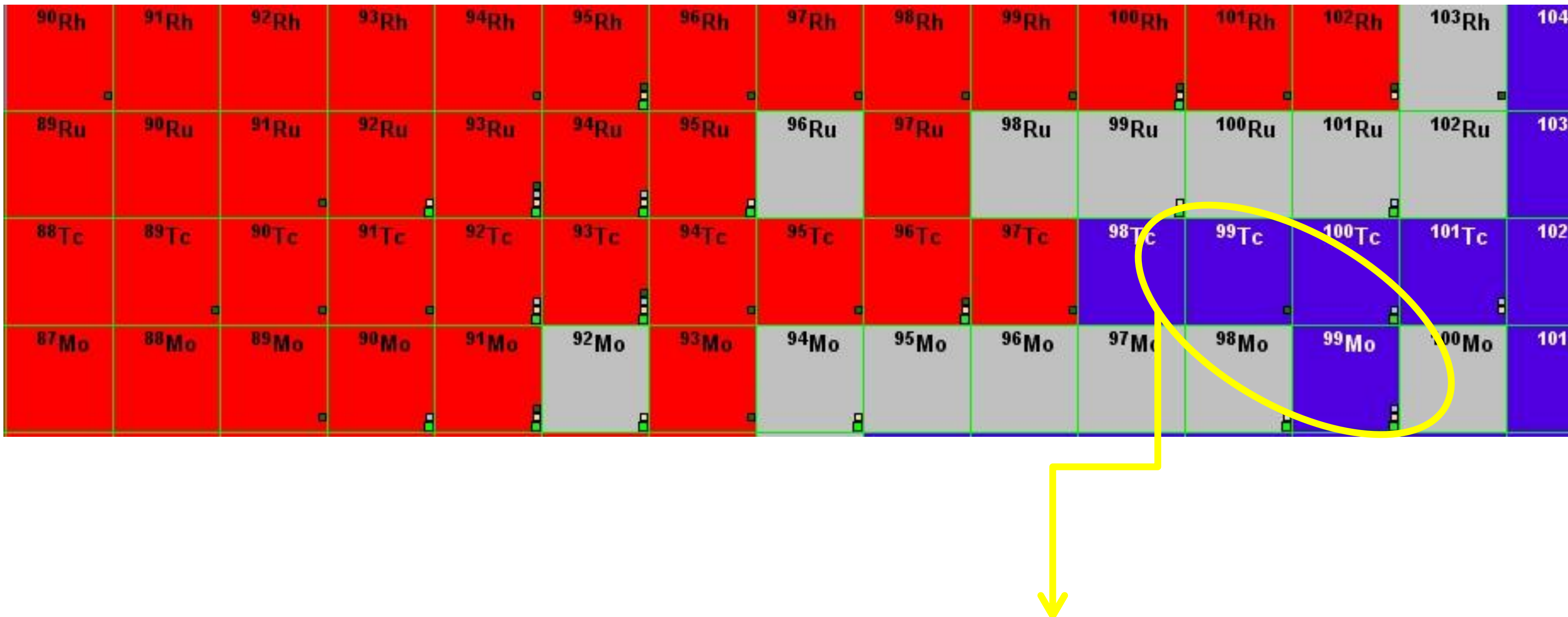



FIG. 1 — Microphotometer tracings of various Tc stars in the regions of the three zero-volt Tc lines: R And (S6, 6e; LPV), RS Cnc (M6S; irregular), HD 35155 (S4, 1; nonvariable), ρ Per (M4 II–III, shown for comparison), UU Aur (N3; C5, 5; semiregular), 19 (TX) Psc (N0; C6, 2; irregular).

Benjamin F. Peery Jr. PASP **83** 1971

# The Case of Technetium

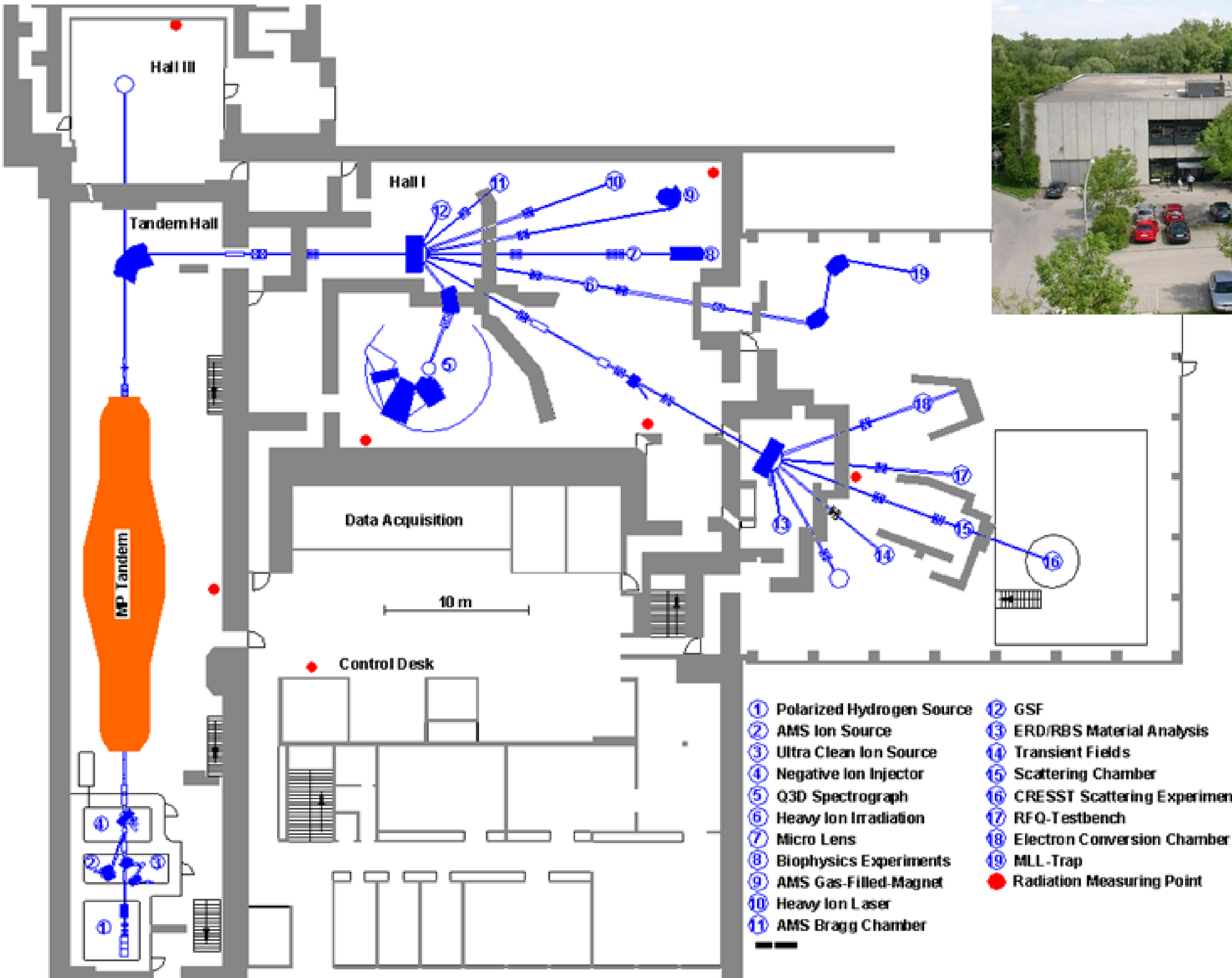



$$t_{1/2} = 2.1 \times 10^5 \text{ yr}$$

Nuclear Astrophysics in your own “back yard”

# EXPERIMENTAL FACILITIES

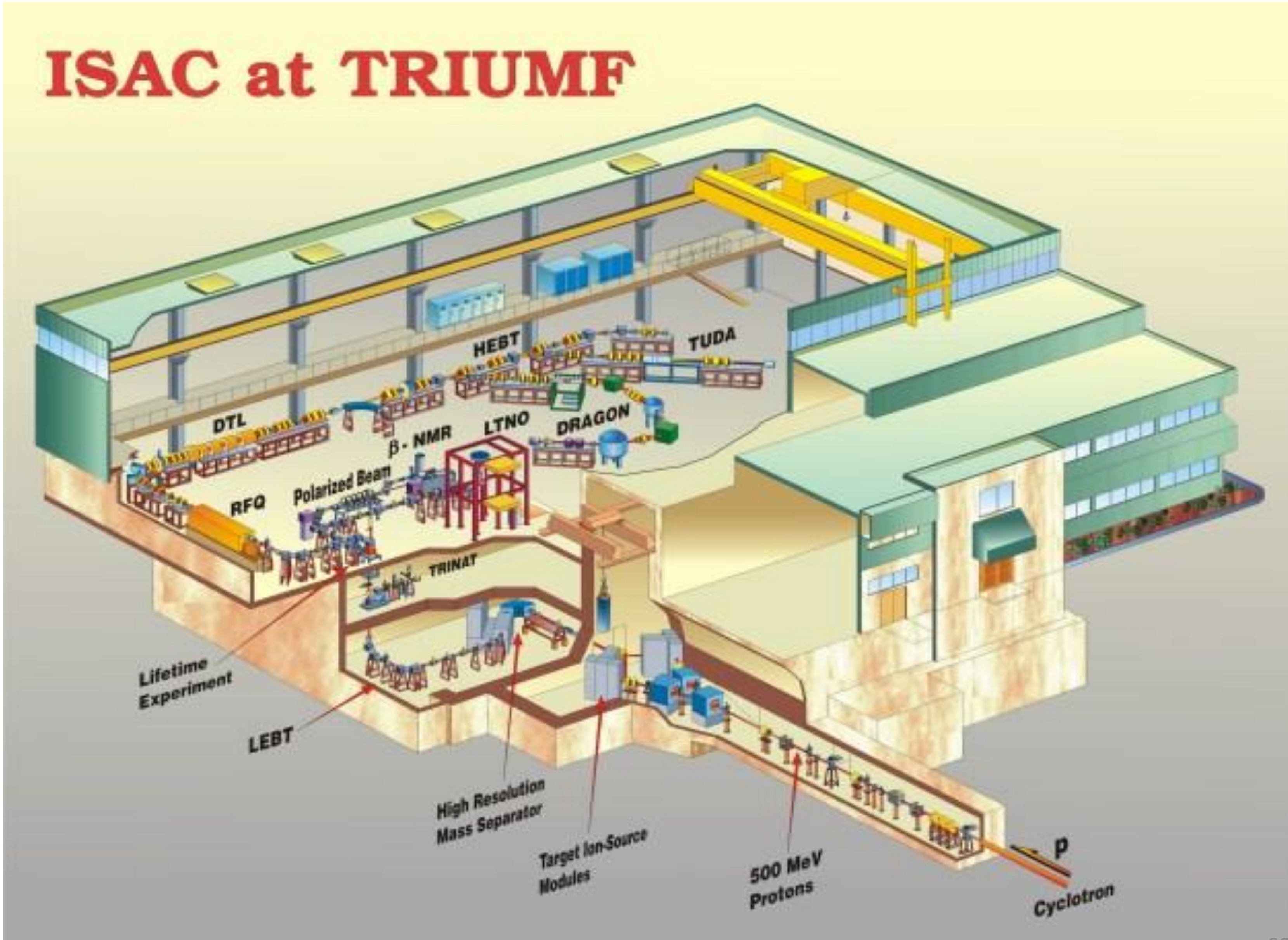
# *Maier-Leibnitz-Laboratorium* (Garching bei München)

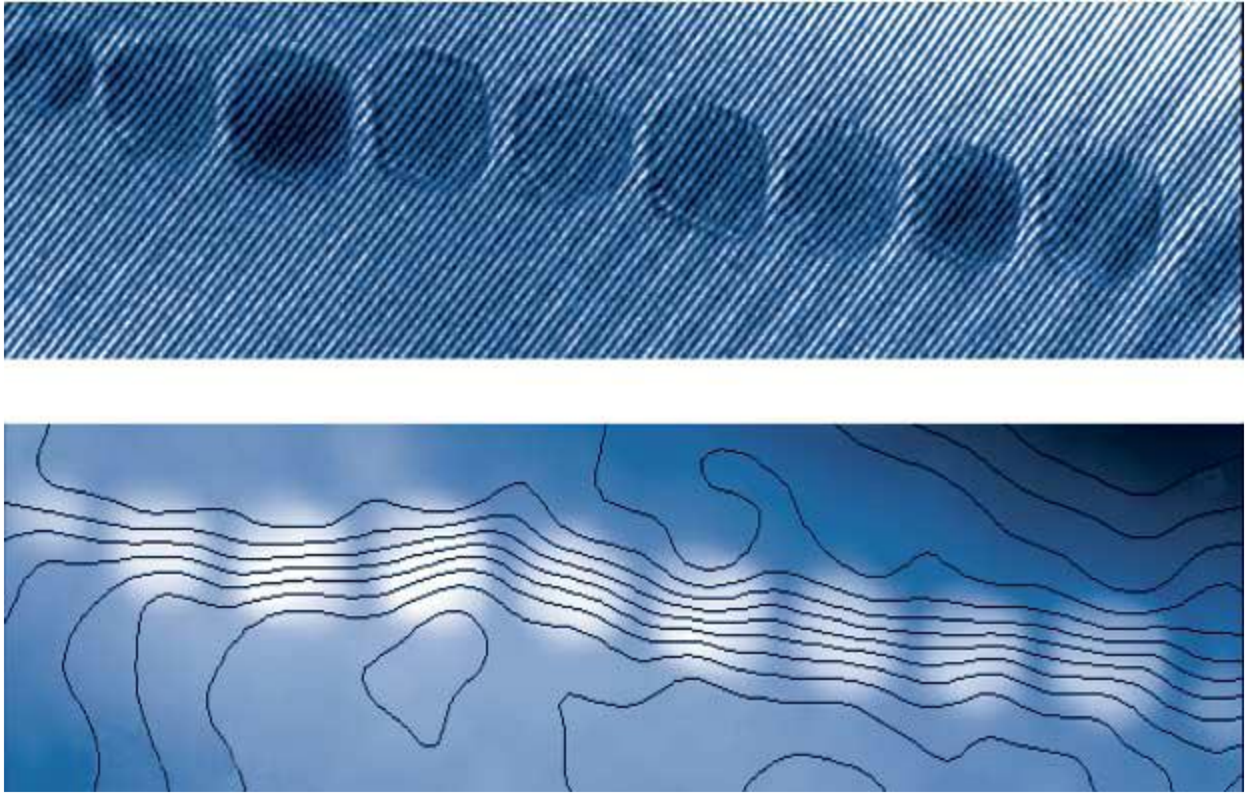



LMU MLL TUM

# MLL Tandembeschleuniger Garching

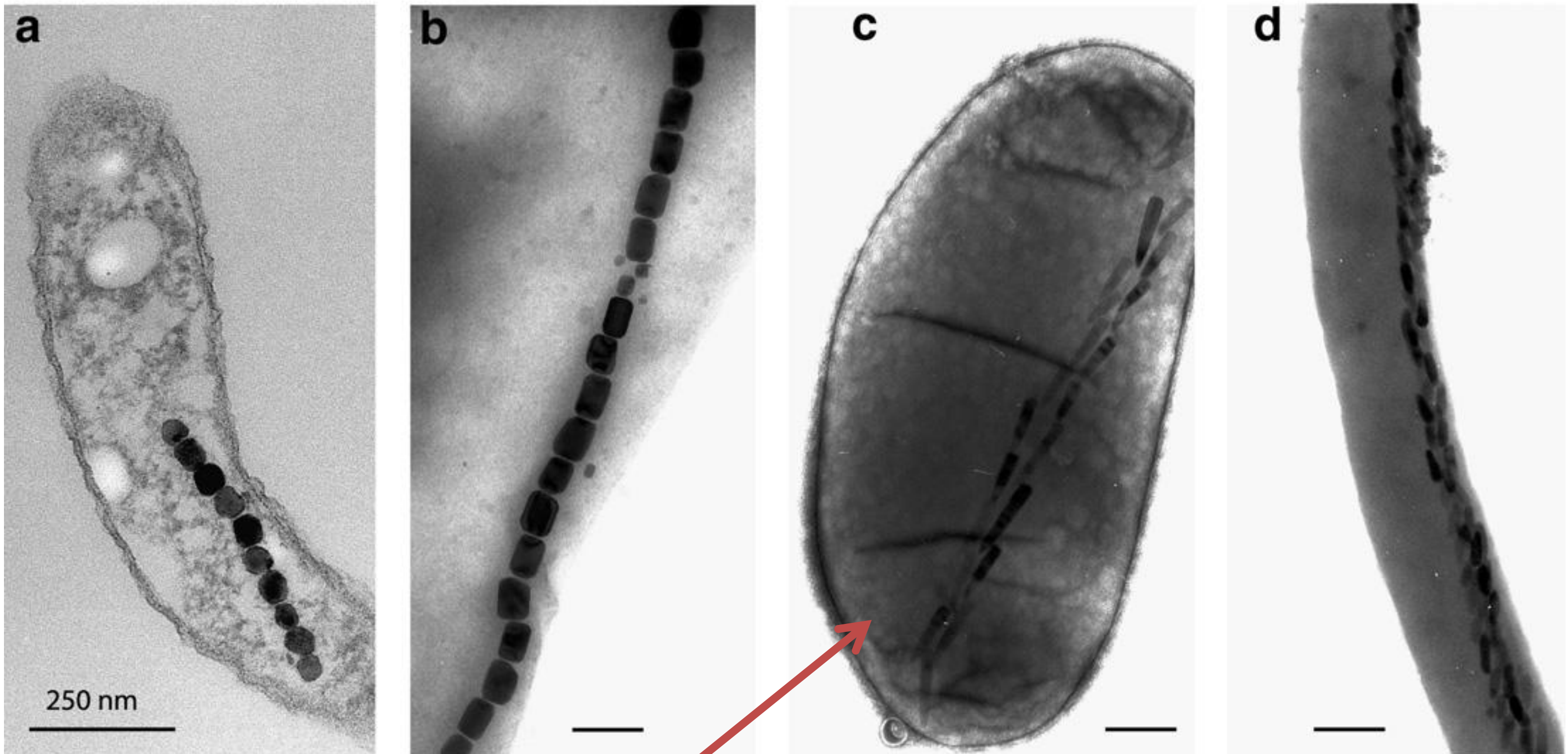
# ISAC in Vancouver, Kanada





Normally, the dead don't talk;  but, perhaps they have left us a message.

# BIOGENIC RECORDS OF SUPERNOVAE



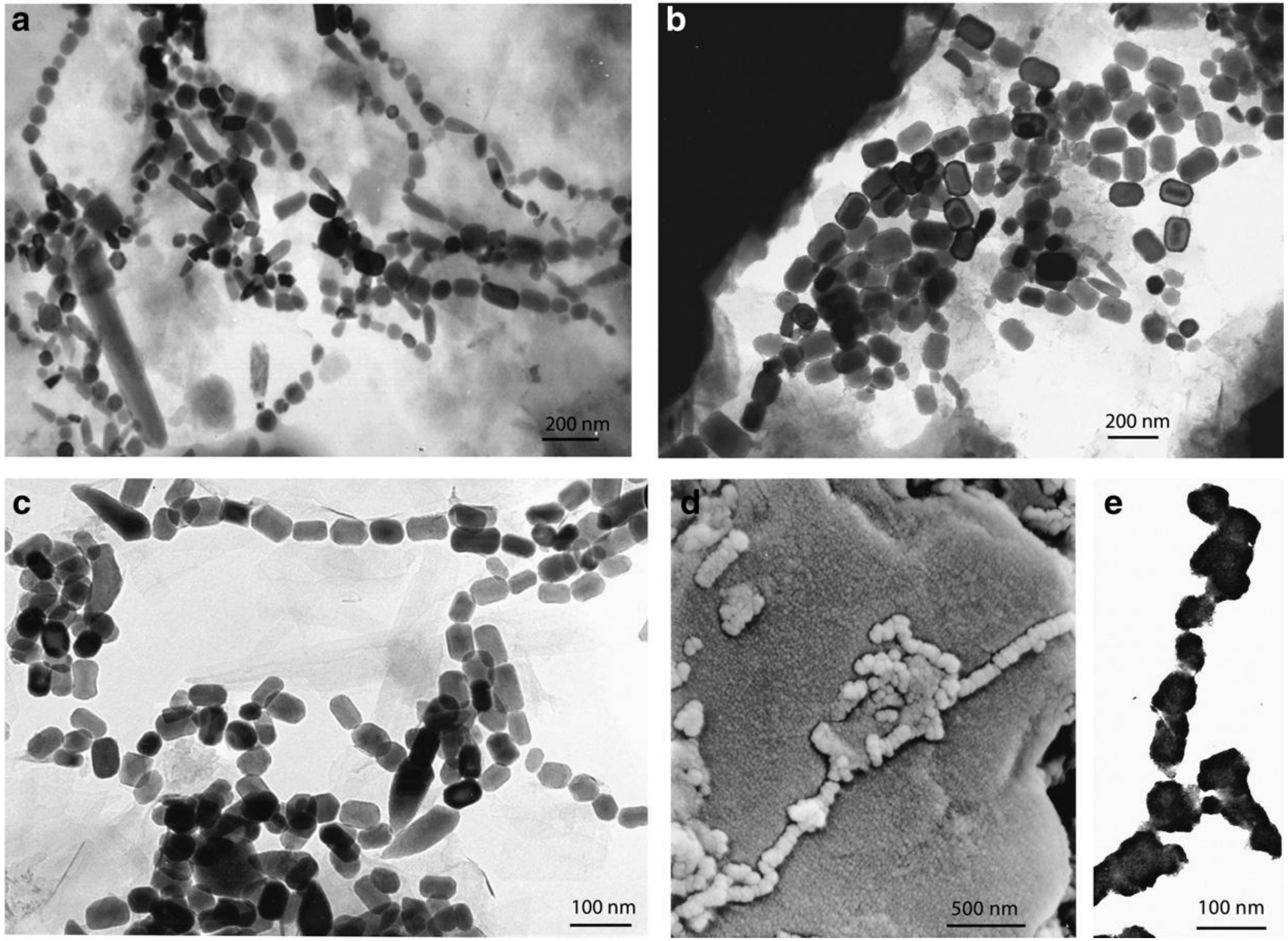

**Magnetotactic Bacteria**

*Magnetobacterium bavaricum*

a) Lab grown strain

b) Lake Ammersee specimen

c) Lake Chiemsee specimen




# Magnetofossils

a) Quaternary Ocean DP fossils
b) Miocene (23-5 My BP) fossils
c) Cretaceous (145-65 Myr) fossils from Culver Cliff chalk
d) Same as c)
e) 1.9 **Gyr** fossils, Ontario Canada