ORIGINS OF THE ELEMENTS

Cameron's perspective

Conversion from nuclear physicist to astrophysicist
  Cameron (1999 ARAA) `that moment marked an instant turning
  point in my career'

-- s-process:
  - suggested 13C(alpha,n)16O as a neutron source. B2FH were not so specific. Cameron's suggestion is now the key neutron source for red giants.
  - calculated neutron capture cross sections (Fig.10.2.3)
  - calculated abundance pattern for different exposures to neutrons (Fig 11.1.1 - 11.1.8)

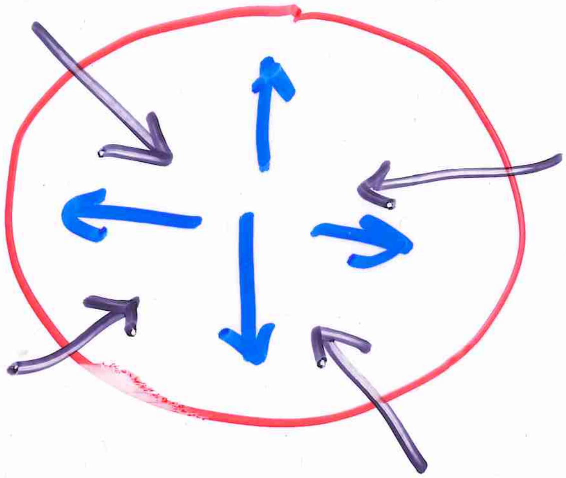
-- Li production from 3He(alpha,gamma)7Be(e-, nu_e)7Li
  - Now called the Cameron-Fowler mechanism and operates in some red giants

-- Heavy ion thermonuclear reactions
  - An early advocate (in CRL-41) for these reactions in very hot dense cores.
    - Hoyle (1954) and Nakagawa et al. (1956) had discussed these reactions.
      See Table 12.1. `Many reactions in which particles are emitted'
      `General result of the heavy ion thermonuclear reactions is to start building nuclei of intermediate weight beyond neon, and to give further contributions to neutron capture on a slow time scale.'
      See my earlier comments on B2FH's alpha-process.

Cameron's PASP summary

Cameron's 1959 Liege figures

(Hoyle 1955 Frontiers of Astronomy fig. 45 46 47)



- Gravity wishes to squash a star
- Higher gas pressure in center opposes gravity (i.e., hotter)
- Energy flows from hot core to cool outside (i.e., starlight) (+ ν losses)
- Nuclear fuel burns to replace lost energy to keep core hot
- **When fuel is exhausted, core collapses → heats up → nuclear ash becomes the new fuel**

Elements are distinguished by

Atomic Number, Z =
Number of protons in the nucleus

- Eighty-one natural elements run from Hydrogen (Z = 1) to Bismuth (Z = 83).
- Technetium (Z = 43) and Promethium (Z = 61) are radioactive and have decayed.
- There are a few naturally occurring radioactive active elements: Uranium (Z = 92) and Thorium (Z = 90) and their decay products.

HYDROGEN, Z = 1

Water, H_2O

Big Bang survivor

HELIUM, Z = 2

Airships, coolant

Earth: Product of U and Th decay

Stars: 90% Big Bang 10% Stars

LITHIUM, Z = 3

Greases, medicine, nuclear bombs

10% Big Bang, 10% Spallation, 80% Red giants, Supernovae II

BERYLLIUM, Z = 4

Alloys, beryl (emeralds)

100% Spallation

BORON, Z = 5

Pyrex, bleaches, fireproofing

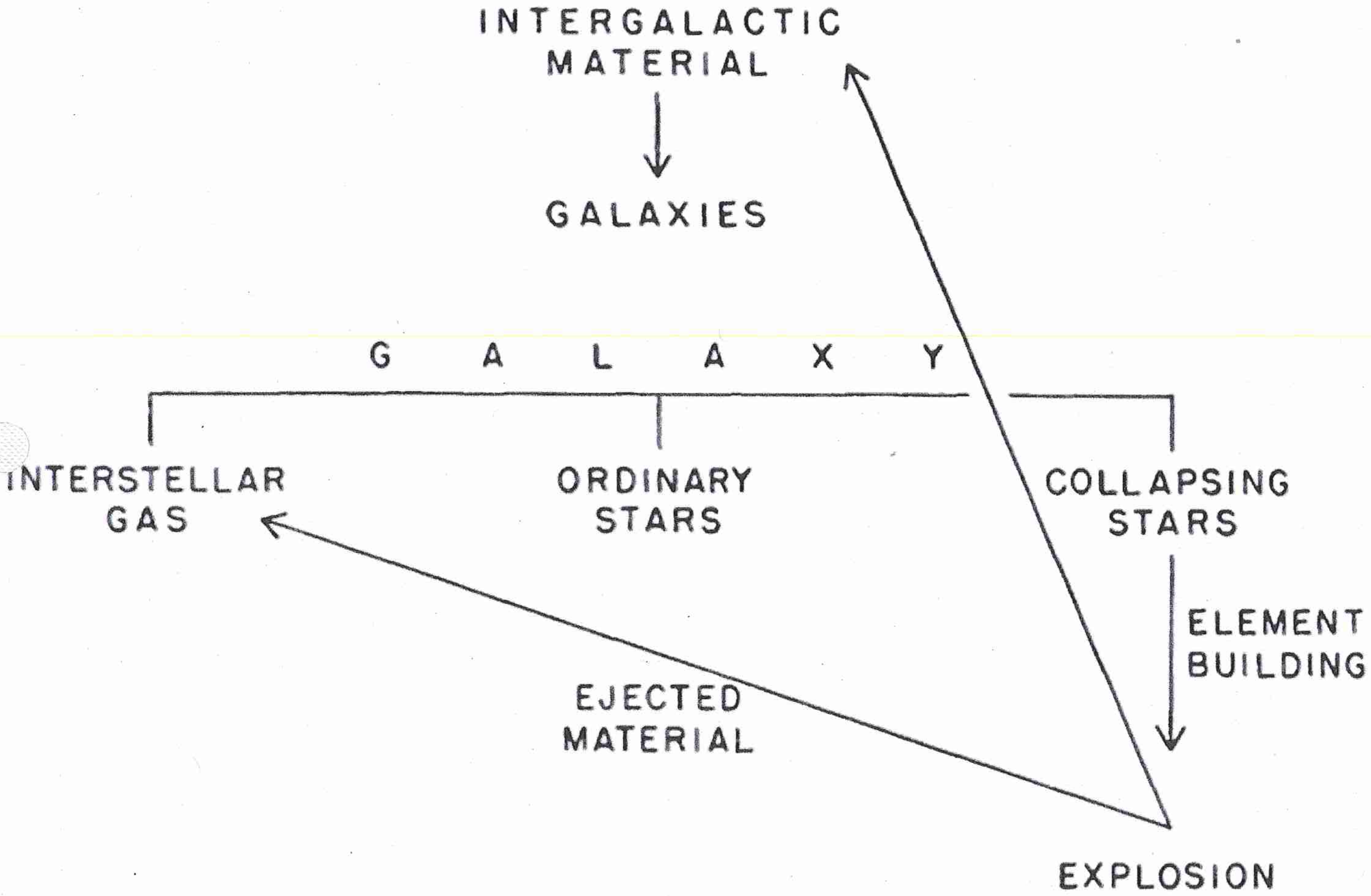
30% Spallation, 70% Supernovae II (?)

CARBON, Z = 6 to **NICKEL, Z = 28**:

- Lighter elements – Carbon to Silicon – primarily from massive stars and their supernovae (Type II)
- Heavier elements – Silicon to Nickel – primarily from exploding white dwarfs (Supernovae of Type Ia)

Beyond nickel, elements are made by neutron captures on iron:

- **BARIUM, Z = 56**
  X-ray medicine, spark plugs
  Red Giants
- **EUROPIUM, Z = 63**
  Red phosphor in TVs
  Supernovae Type II ?
- **GOLD, Z = 79**
  Precious metal
  Red giants and Supernovae Type II ?



Hoyle, 1954, ApJS, 1, 121
On nuclear reactions occurring
in very hot stars I. The Synthesis
of Elements from Carbon to Nickel

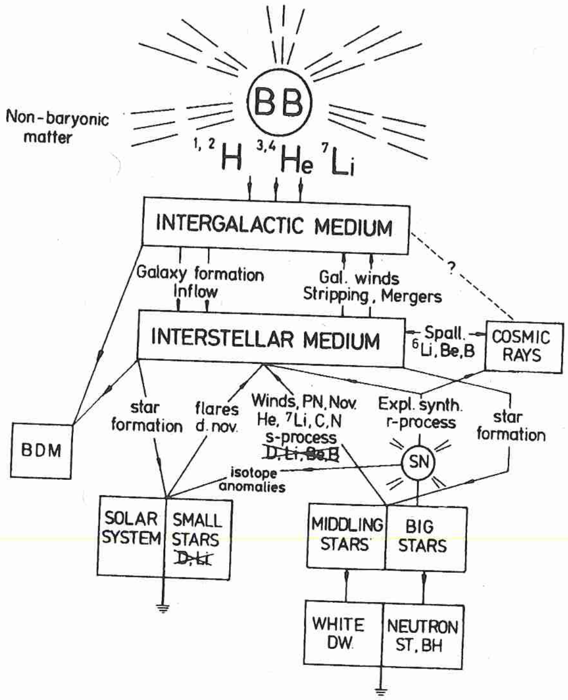


Fig. 1.1. A scenario for cosmic chemical evolution, adapted from Pagel (1981).

COMPOSITIONS OF ASTRONOMICAL OBJECTS

NOTATION

Number Density

One may express number density of an element or isotope
with respect to H:

A(El) = N(El)/H and astronomers often puts thi on a log scale

log e(A_El) = log A(El) + 12.00

where 12.00 has historical origins.

For convenience, it is often useful to express abundances in
astronomical objects with respect to
the Sun/Standard Abundance Distribution:

[X] = logX - logX(Sun)

Beware! Different authors likely adopt different logX(Sun).
Others may reference [X] to a source other then the Sun.
And others (in particular, theoreticians!!) may define [X]
differently.

[Fe/H] = -1.3 This star has an under/overabundance of Fe relative to the Sun by a factor of ??

If a star has [Mg/Fe] =+0.3 and a [Fe/H] = -1.1, what is its [Mg/H]?

COMPOSITIONS OF ASTRONOMICAL OBJECTS

NOTATION

Mass Fraction

Theoreticians, especially those concerned with stellar evolutionary calculations, often prefer to quote abundances in terms of mass fractions.

At the simplest level:

X = Mass fraction of H
Y = Mass fraction of He
Z = Mass fraction of all other elements

where $X + Y + Z = 1$

(In astronomy, one customary refers to all elements beyond He as a `metals')

Z can obviously be broken down into Z for individual elements, say as Z(O) and Z(Mg).

The latest compilation of the SAD (Lodders et al. 2009 Landolt–Boernstein, New Series Vol. V1/4B Chapter 4.4) gives

$X = 0.7390$ $Y = 0.2469$ $Z = 0.0141$

But Big Bang nucleosynthesis results (see later) in approximately
$X = 0.75$ $Y= 0.25$ $Z = 0$

This would seem to suggest that, as the Galaxy (and whatever went before) built up the Sun's Z the He mass fraction was lowered.

One major factor is that He has diffused or settled out of the solar atmosphere. This has been estimated to be a 15% effect over the 4.6 Gyr life of the Sun. Or the early/protoSun had

$X = 0.7112$ $Y = 0.2735$ $Z = 0.0153$

But it's clear that Galactic He has increased very little in abundance since the Big Bang.

(see Lodders et al.'s Table 8 for a list of the principal contributors to Z.)

(You may wish to check your understanding of mass fractions by calculating X Y and Z from Lodders et al.'s Table 10.)

Table 7. Present-day solar mass fractions and He abundance

Present-Day:	Z/X	X	Y	Z	A(He)
this work	0.0191	0.7390	0.2469	0.0141	10.925
[05A1], [07G]	0.0165	0.7392	0.2486	0.0122	10.93
[98G]	0.0231	0.7347	0.2483	0.0169	10.93

Table 9. Protosolar mass fractions and He abundance at the beginning of the solar system 4.56 Ga ago

	Z_0/X_0	X_0	Y_0	Z_0	$A(He)_0$
this work [a]	0.0215	0.7112	0.2735	0.0153	10.986
[05A1], [07G] [b]	0.0185	0.7133	0.2735	0.0132	10.985
[98G] [c]	0.0231	0.7086	0.2750	0.0163	10.99
[89A]	0.0267	0.7068	0.2743	0.0189	10.99

[a] Conversion of present-day to protosolar: $A(He)_0 = A(He) + 0.061$ dex, all other elements (except H) $A(X)_0 = A(X) + 0.053$ dex

[b] $A(He)_0 = A(He) + 0.057$ dex, all other elements (except H) $A(X)_0 = A(X) + 0.05$ dex.

[c] No diffusion effect on Z, $Z/X = Z_0/X_0$; (~10% loss of He).

Table 2. Observed CI-chondrite falls

Meteorite	Date of fall	Country	Preserved mass
Alais	15 March 1806	France	6 kg
Ivuna	16 Dec. 1938	Tanzania	0.7 kg
Orgueil	14 May 1868	France	14 kg
Revelstoke	31 March 1965	Canada	<1 g
Tonk	22 Jan. 1911	India	10 g

Table 8. Present-day solar composition (mass %)

	this work	[05A1,07G]	[98G]
H (=X)	73.90	73.92	73.47
He (=Y)	24.69	24.86	24.83
O	0.63	0.54	0.79
C	0.22	0.22	0.29
Ne	0.17	0.10	0.18
Fe	0.12	0.12	0.13
N	0.07	0.06	0.08
Si	0.07	0.07	0.07
Mg	0.06	0.06	0.07
S	0.03	0.03	0.05
all other elements	0.04	0.02	0.04
total heavy elements (=Z)	1.41	1.22	1.69

COMPOSITIONS OF ASTRONOMICAL OBJECTS

Notation -- Meteorites

H (and He etc.) have largely escaped from meteorites so that abundances cannot be measured with respect to H.

The standard became Si and its abundance in a sample was set at 10^6 (as in Lodders et al.'s Table 10).

The question then arises as to how to normalize meteoritic (say from CI1 carbonaceous chondrites) to solar photospheric abundances obtained spectroscopically where El/H is a NATURALLY obtained quantity (see later). This normalization is done using one or more elements whose abundances are obtained from both meteorites and the solar photosphere with great accuracy.

Lodders et al. take an extreme but laudable approach: take an average normalization from the 39 elements whose solar abundances are within 0.1 dex of the normalized meteoritic abudances. The log of the average ratio of solar abundance per 10^12 H atoms to the meteoritic abundance per 10^6 Si atoms is 1.533+/-0.042 or loge(Si)= 7.533.

For small abundance anomalies such as may be found for presolar grains in meteorites, a `delta' notation has been introduced. For example,

delta (X) = [X_meas/X_std - 1] x 1000

This expresses the deviation in parts per thousand (permil or 0/00). For very small deviations, I have seen epsilon(X) in parts per ten thousand or 0/000.

Discussions of presolar grains tend to interweave in the text plots of isotopic ratios vs isotopic ratios and plots of delta(isotopic ratio) vs delta(isotopic ratio). Take care!

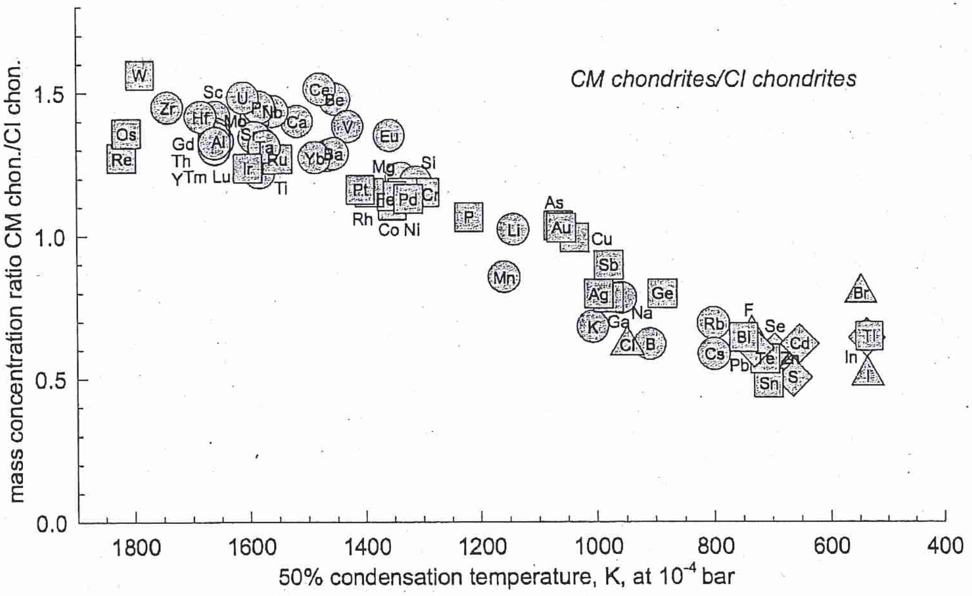


Fig. 2. Mass concentration ratios of the elements in CM-chondrites over CI-chondrites as a function of condensation temperature. CI-chondrites have the highest concentrations of moderately volatile and highly volatile elements. All other groups of meteorites are lower. The smooth decline in abundance ratios with condensation temperature irrespective of the geochemical character of the elements suggests volatility controlled abundances in CM-chondrites. The symbol shape indicates the geochemical character of the element: square = siderophile, circle = lithophile, diamond = chalcophile, triangle = halogen.

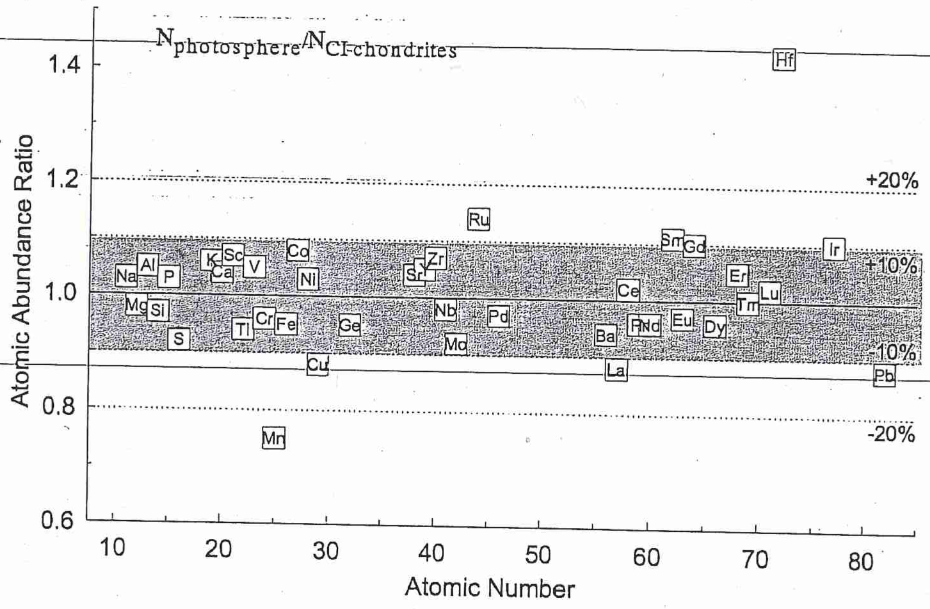
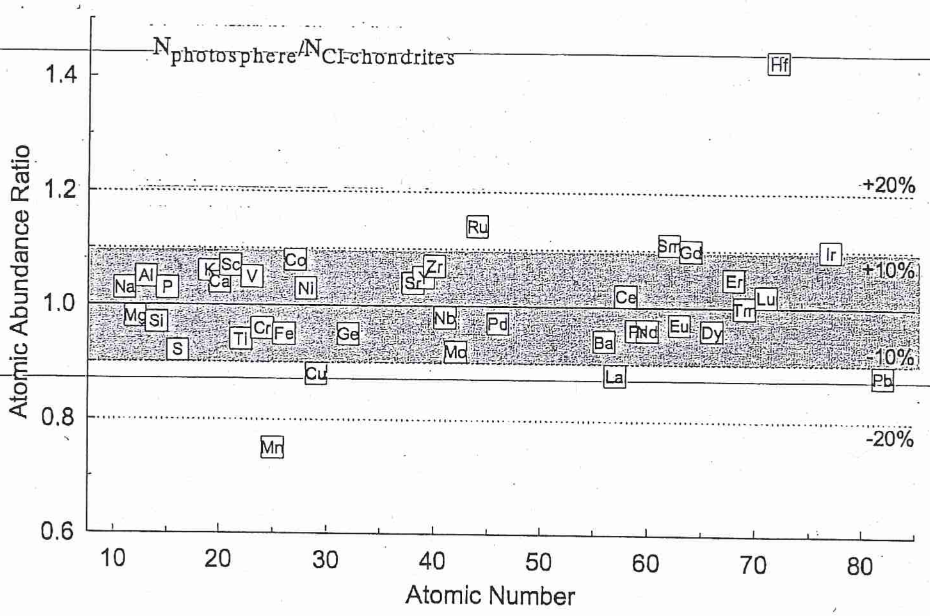


Fig. 4. Comparison of photospheric and CI-chondrite abundances, excluding highly volatile elements. Only elements with uncertainties below ~ 25% (<0.10 dex) in the photospheric abundance determinations are shown. The grey-shaded area is for elements that agree within ±10%; the range for 20% agreement is shown by the other dotted lines. Hafnium and Mn are well determined in meteorites and in the Sun, but differ by more than 30 %. Lithium and Be would also qualify for inclusion in this diagram but are not included. Lithium is by a factor of more than 100 higher in meteorites, because it is destroyed in the interior of the Sun by nuclear reactions. Beryllium only differs by 15%, suggesting less or no destruction by nuclear reactions.



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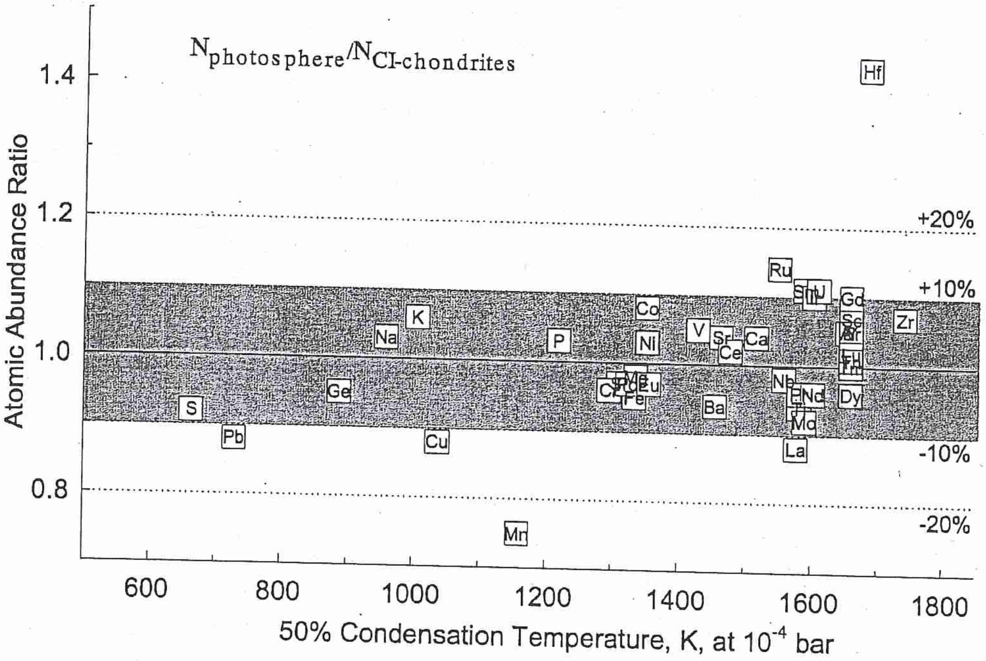


Fig. 5. Same as Fig. 4, but abundance ratios are plotted as function of 50% condensation temperatures. The agreement between solar and meteoritic abundances is independent of the volatility of the elements.

CAMERON (1957)

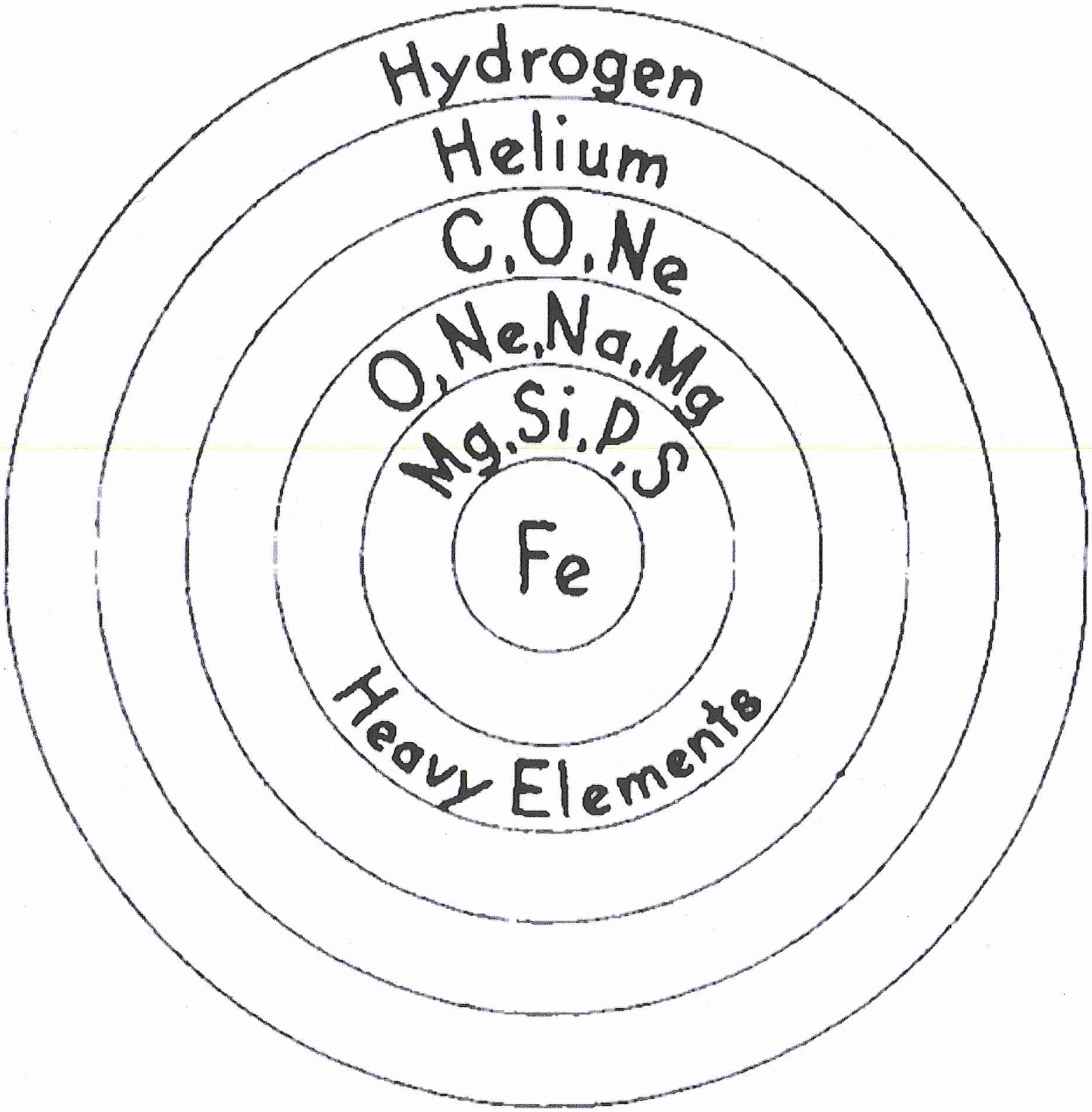
Elements	Method of Formation
D, Li, Be, B	Not formed in stellar interiors. Possibly made by nuclear reactions in stellar atmospheres
He, C, N, O, F, Ne	Hydrogen and helium thermonuclear reactions in orderly evolution of stellar interiors
Ne to Ca	1. Heavy-ion thermonuclear reactions in orderly evolution of stellar interiors 2. Neutron capture on slow time scale 3. Hydrogen and helium thermonuclear reactions in supernova explosions
Fe peak	Statistical equilibrium in pre-supernovae and in supernovae
Heavy elements:	
(*a*) Unshielded	Neutron capture on fast time scale in Type I supernovae
(*b*) Shielded	Neutron capture on slow time scale in orderly evolution of stellar interiors
(*c*) Excluded	1. Proton capture and photonuclear reactions in Type II supernovae 2. Photonuclear reactions on slow time scale in orderly evolution of stellar interiors
(*d*) Trans-bismuth	Neutron capture on fast time scale in Type I supernovae

Nakagawa et al.
1956 Prog. Theor. Phy. 16 389

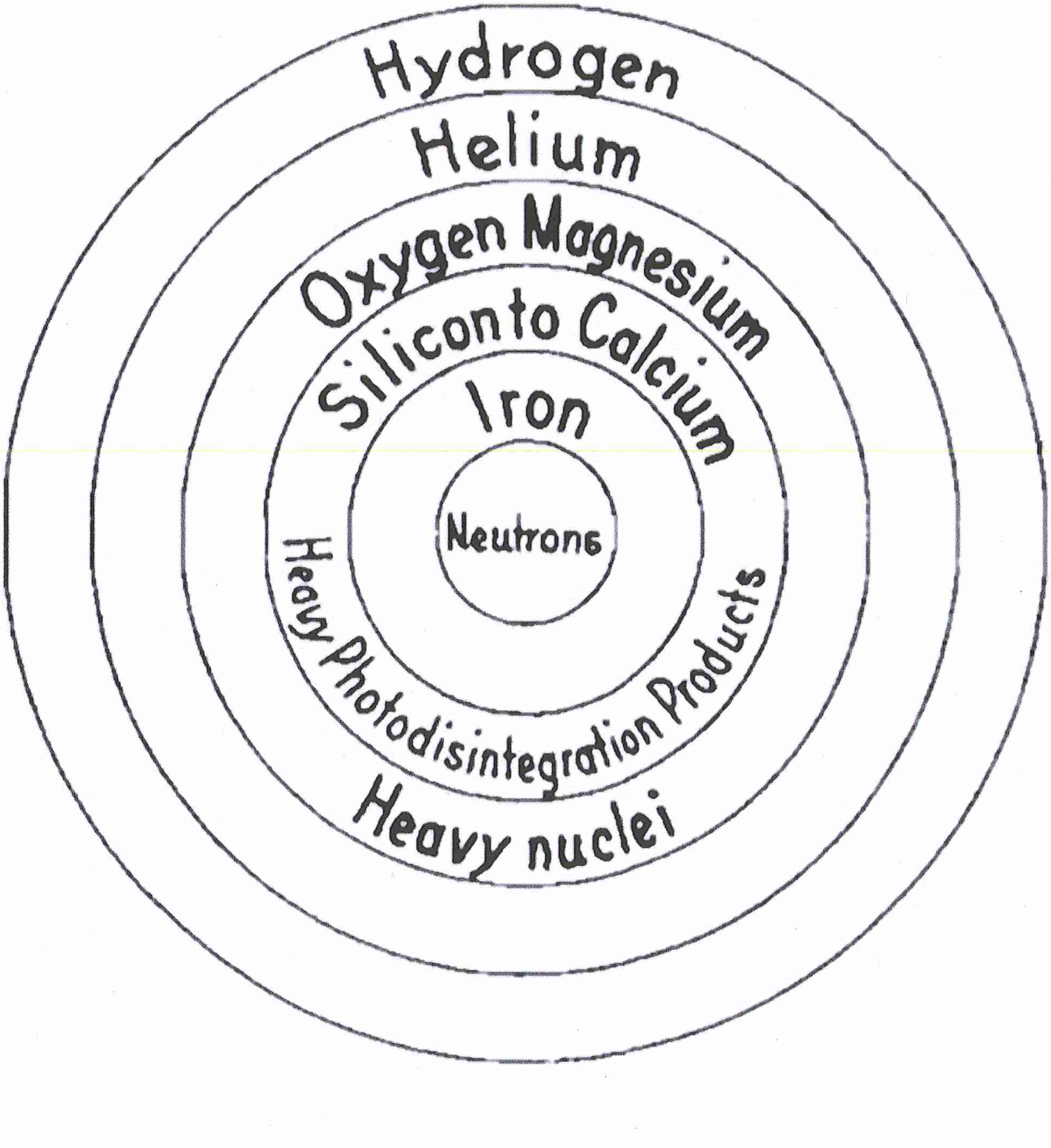
TABLE 12.1

EXOTHERMIC HEAVY ION REACTIONS

Bombarding Particles	Products	Energy Release
$C^{12} + C^{12}$	$\gamma + Mg^{24}$	13.95 Mev
	$p + Na^{23}$	2.25
	$\alpha + Ne^{20}$	4.62
$C^{12} + O^{16}$	$\gamma + Si^{28}$	16.8
	$p + Al^{27}$	5.21
	$\alpha + Mg^{24}$	6.80
$C^{12} + Ne^{20}$	$\gamma + S^{32}$	19.0
	$n + S^{31}(\beta^+ \nu)P^{31}$	4.2
	$p + P^{31}$	10.1
	$\alpha + Si^{28}$	12.0
	$Be^8 + Mg^{24}$	2.0
	$O^{16} + O^{16}$	2.4
$O^{16} + O^{16}$	$\gamma + S^{32}$	16.6
	$n + S^{31}(\beta^+ \nu)P^{31}$	1.8
	$p + P^{31}$	7.7
	$\alpha + Si^{28}$	9.7
$O^{16} + Ne^{20}$	$\gamma + A^{36}$	18.5
	$n + A^{35}(\beta^+ \nu)Cl^{35}$	3.8
	$p + C^{35}$	10.0
	$\alpha + S^{32}$	11.8
	$Li^5 + P^{31}$	1.2
	$Be^8 + Si^{28}$	4.8
	$C^{12} + Mg^{24}$	2.2
$Ne^{20} + Ne^{20}$	$\gamma + Ca^{40}$	20.9
	$n + Ca^{39}(\beta^+ \nu)K^{39}$	5.0
	$p + K^{39}$	12.5
	$d + K^{38}$	1.5
	$He^3 + A^{37}(e, \nu)Cl^{37}$	2.0
	$\alpha + A^{36}$	13.7
	$Li^5 + Cl^{35}$	3.4
	$Be^8 + S^{32}$	7.0
	$C^{12} + Si^{28}$	7.4
	$O^{16} + Mg^{24}$	4.6



Cameron 1959



Cameron 1959

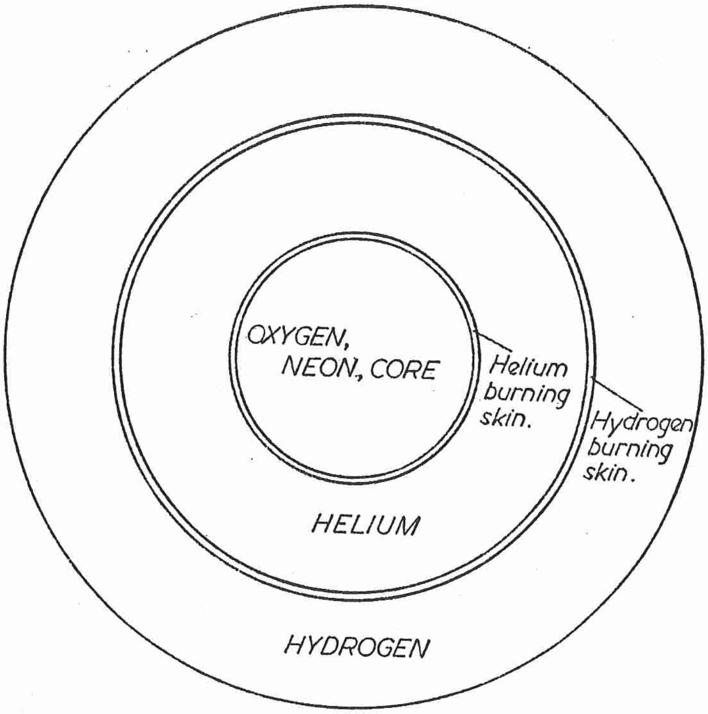


FIG. 45.

Hoyle
1955
Frontiers
of
Astronomy

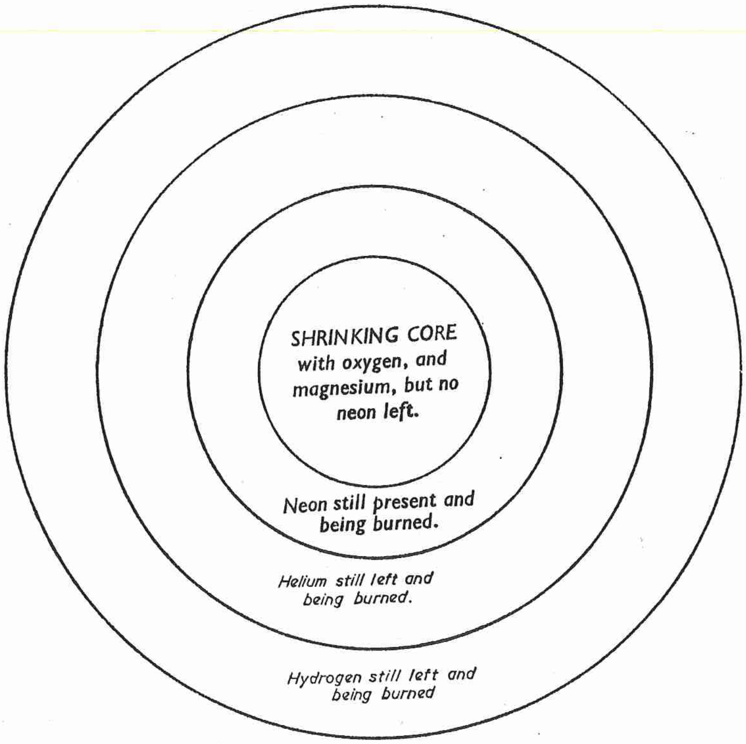


FIG. 46. Schematic drawing of a four-zoned star.

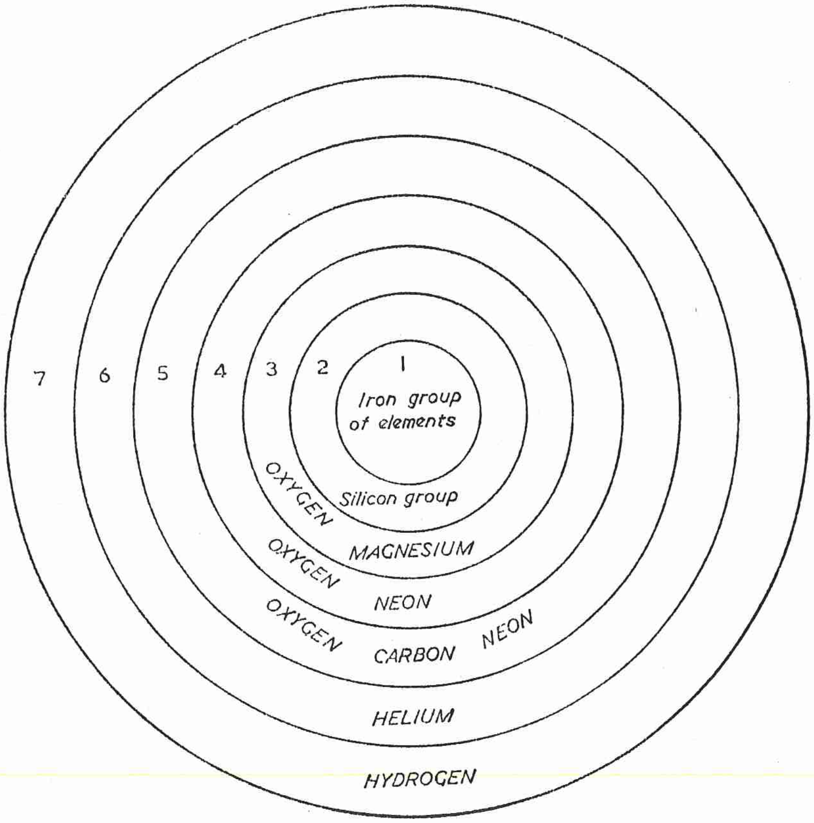
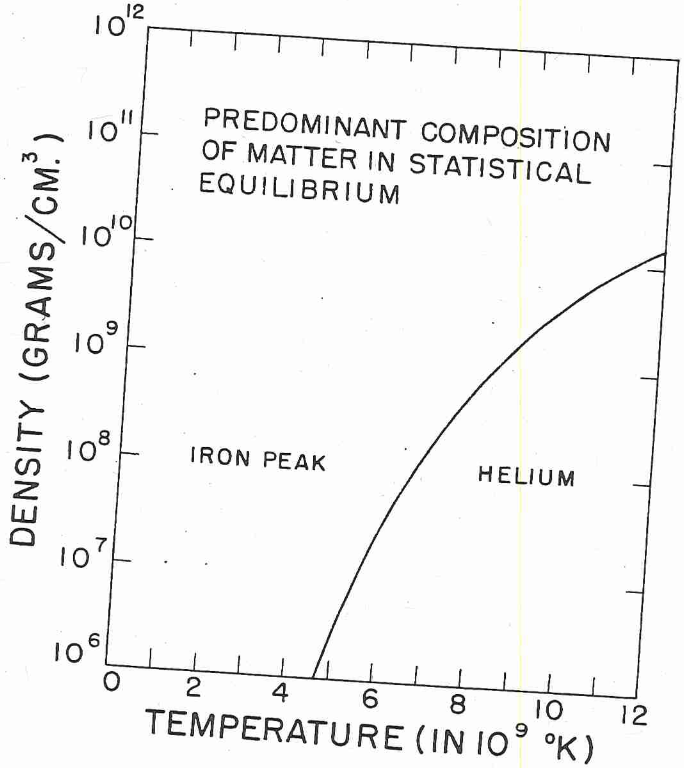


FIG. 47. Schematic drawing of a seven-zoned star.

From Cameron (CRL-41)
after Hoyle (1946, MNRAS, 106 366)



Regions in the temperature-density diagram in which the material is mostly in the form of the iron peak or of He^4.

ORIGIN OF THE ELEMENTS`

Looking back to 1957, I am impressed by two very striking aspects of both the B2FH and Cameron papers.

-- 1. They are comprehensive surveys with a remarkable degree of originality, that is they are NOT reviews of an extensive literature on the topic;

-- 2. Both are based primarily on theoretical forays into astrophysics and in particular nucelar astrophysics
 - a term possibly coined by Cameron.

Observations of stars and other extra-solar objects play a VERY small part in these seminal papers.

In large measure, this reflected the almost complete lack of information on chemical compositions of astronomical objects.

Here is a brief review of the observational data considered by B2FH

1. Cosmic abundances Based on a compilation by Suess & Urey (1956). Very largely drawn from meteorites as suggested earlier by Urey.

2. SN lightcurves and comparison with predicted radioactive energy releases with claim that Cf-254 was a major source

3. Qualitative evidence for H-burning and He-burning from He-rich hot stars, Wolf-Rayet stars, white dwarfs, carbon stars with some showing a low 12C/13C ratio and a rough analysis of a Barium star where s-process products are enhanced; these are K giants with enrichments of heavy elements akin to those seen in the S stars and cooler stars where Merrill found Tc.
    -See Merrill's abstract.
    -Why were Ba stars and not S stars chosen for this first analysis?

Discussion also covered peculiar A stars on the hypothesis that their PECULIAR spectra/compositions could be attributed to `element synthesis in the surfaces of stars'. Some types of Ap stars were by 1957 known to host strong magnetic fields. But synthesis has fallen by the way in favor of diffusion BUT!

4. Chemical evolution of the Galaxy -- then, no observational data!

5. Cosmochronology via U and Th --> age of r-process elements and found age greater than age of solar system and Sun!

1952ApJ...116...21M

SPECTROSCOPIC OBSERVATIONS OF STARS OF CLASS S

Paul W. Merrill
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington
California Institute of Technology

Received February 27, 1952

ABSTRACT

This paper presents a brief survey of S-type spectra based largely on spectrograms with dispersion 9 A/mm of eight stars obtained by I. S. Bowen with the 200-inch telescope. The intensities of several groups of absorption lines and bands and of the more important emission lines are compared in various stars. Radial velocities from both bright and dark lines and a supplementary list of absorption lines identified in the green region are included. The remarkable behavior of certain bright lines of *V* I and of *Cr* I in the spectrum of R Cygni is described.

THE POSSIBLE IDENTIFICATION OF PROMETHIUM IN HR 465

Margo F. Aller and Charles R. Cowley
University of Michigan, Ann Arbor

Received September 19, 1970; revised October 14, 1970

ABSTRACT

Evidence is presented for the possible presence of Pm in the Ap star HR 465.

Is there Promethium in HR 465?

Ove Havnes
Institute of Theoretical Astrophysics
University of Oslo, Norway

E. P. J. van den Heuvel
Astronomical Institute, Utrecht, the Netherlands and Astrophysical Institute, Vrije Universiteit Brussels
Belgium

Received November 23, 1971

A rediscussion of the probability for chance coincidences between laboratory wavelengths and wavelengths in a stellar spectrum shows that the identification of Pm II lines in the spectrum of HR 465 may be due to chance.

Key words: **element identification - HR 465 - peculiar A stars - promethium**

Comments on the Paper «Is there Promethium in HR 465?»

Margo F. Aller and Charles R. Cowley
University of Michigan, Ann Arbor, Michigan

Received January 25, 1972

A discussion of the data presented in the paper "Is there promethium in HR 465" by Havnes and van den Heuvel is given.

Key words: **promethium — HR 465 — line identification**

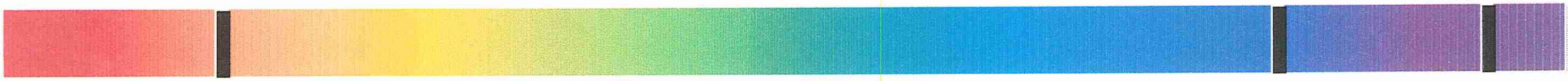
COMMENTS ON THE IDENTIFICATION OF PROMETHIUM IN HR 465

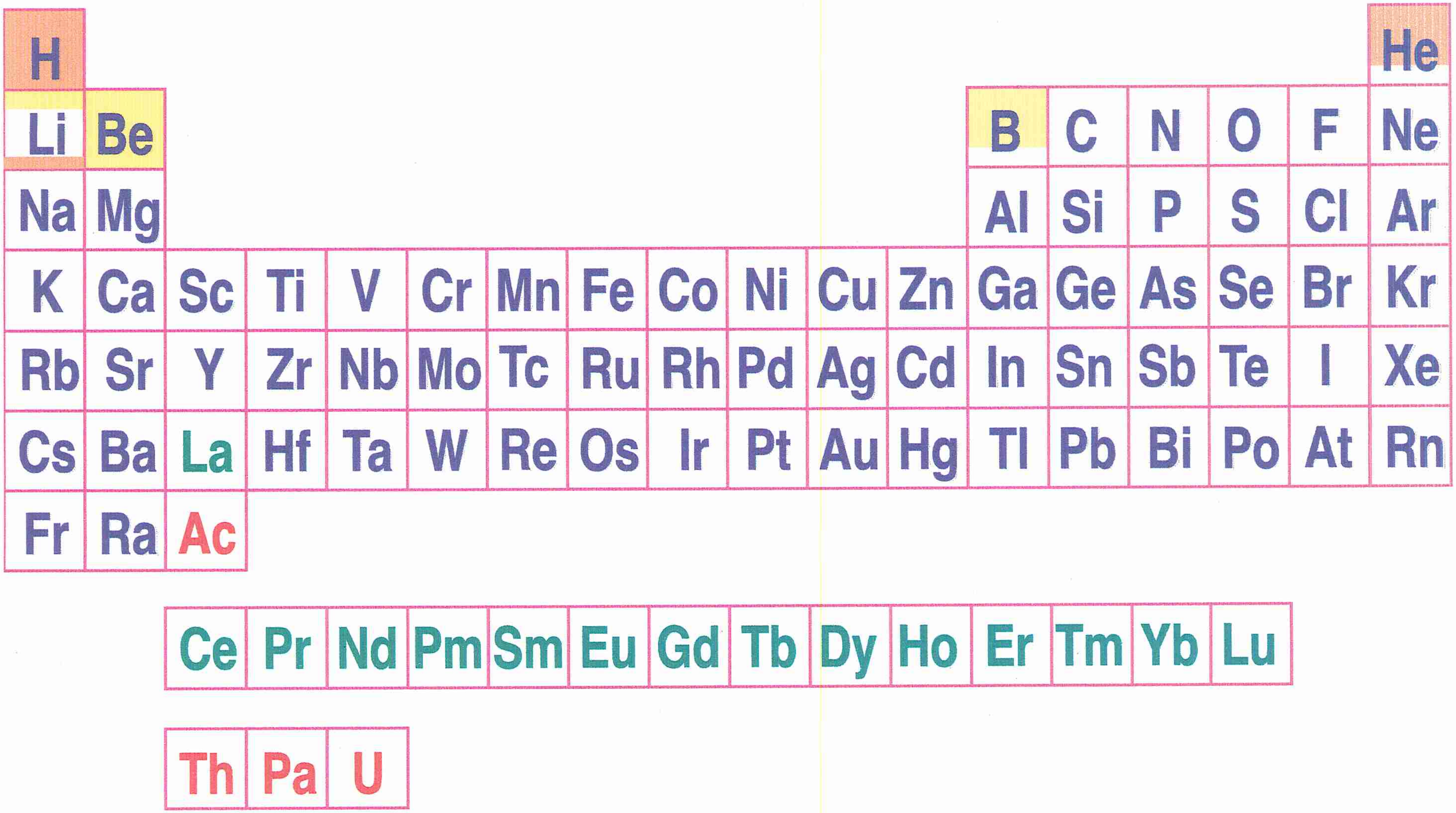
Charles R. Cowley and Margo F. Aller
University of Michigan, Ann Arbor

Received 1972 January 19; revised 1972 February 14

ABSTRACT

The general principles of line identification are discussed in connection with the identification of promethium in HR 465. It is shown that the Russell-Bowen formalism for the significance of wavelength coincidences is improper for most wavelength lists. An alternative procedure, due to F. Upton
to HR 465, resulting in a 2 σ significance level for the
the character of the





H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															
		Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
		Th	Pa	U													

🟧 **Big Bang**

🟨 **Cosmic Rays**

☐ **Stars**