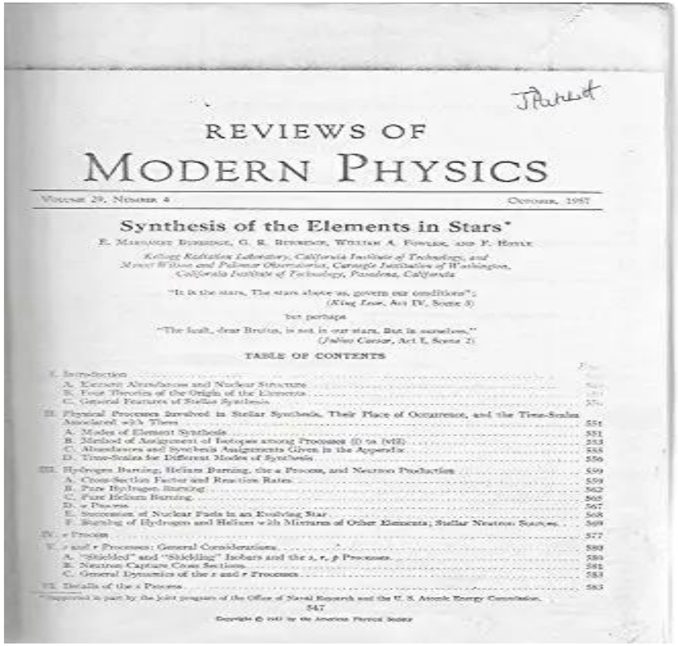
Nucleosynthesis of heavy chemical species revisited

Jean Audouze (IAP)

1957

The year of Sputnik Launch and of B2FH

The very famous B2FH



REVIEWS OF
MODERN PHYSICS

Volume 29, Number 4 October, 1957

Synthesis of the Elements in Stars*

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"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

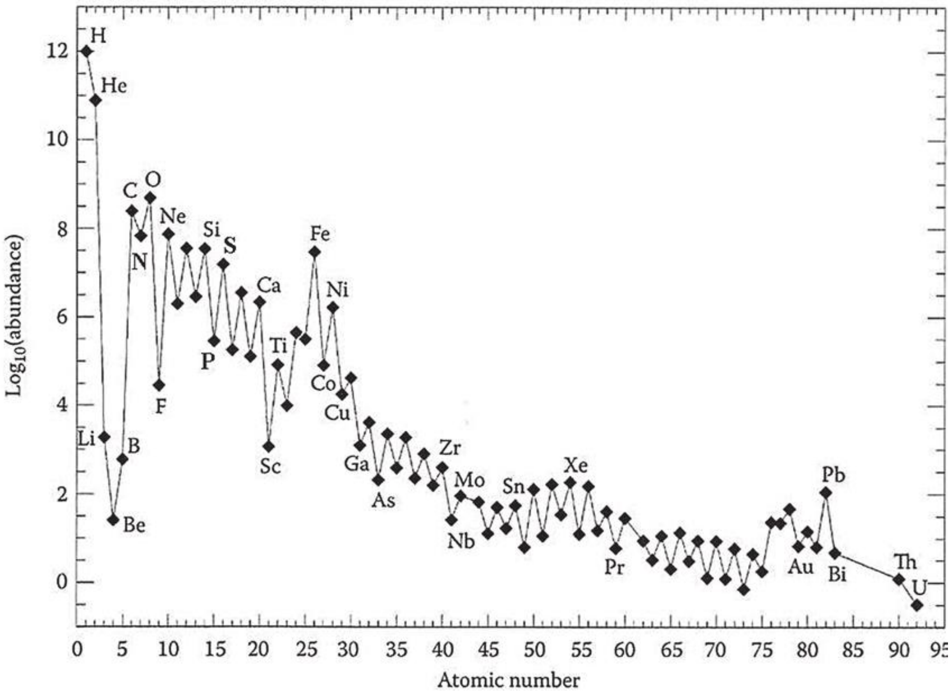
TABLE OF CONTENTS

* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

1952 : observations of Technetium Stars

- Detection of Tc lines in the spectrum of R Geminorum by Paul W. Merrill (ApJ July 1952)
- Life time of Tc 98 : 4.2 My
- First proof of nucleosynthesis occuring in stars

The abundances of the different chemical species



The main nucleosynthetic processes in stars (I)

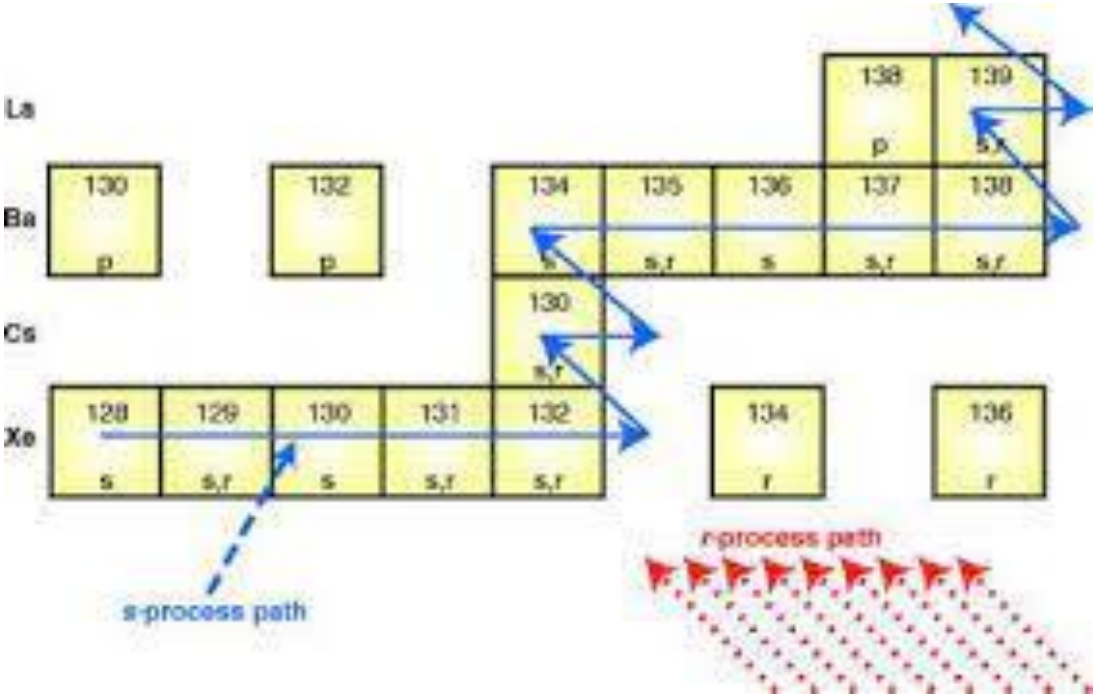
- Thermonuclear fusion reactions responsible of the formation of part of He4 and of chemical species from Carbon to Scandium
- Photodisintegration processes shaping the Iron peak from Scandium to Zinc
- Spallation reactions between RCG and ISM for LiBeB

The main nucleosynthetic processes in stars (II)

- Synthesis of large A nuclear species by neutron absorption processes :

- Slow (s) Process : N = 10(7) cm-3

- Rapid (r) Process : N = 10 (20) cm-3



La
Ba
Cs
Xe
138
p
139
s,r
130
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132
p
134
s
135
s,r
136
s
137
s,r
138
s,r
130
s,r
128
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129
s,r
130
s
131
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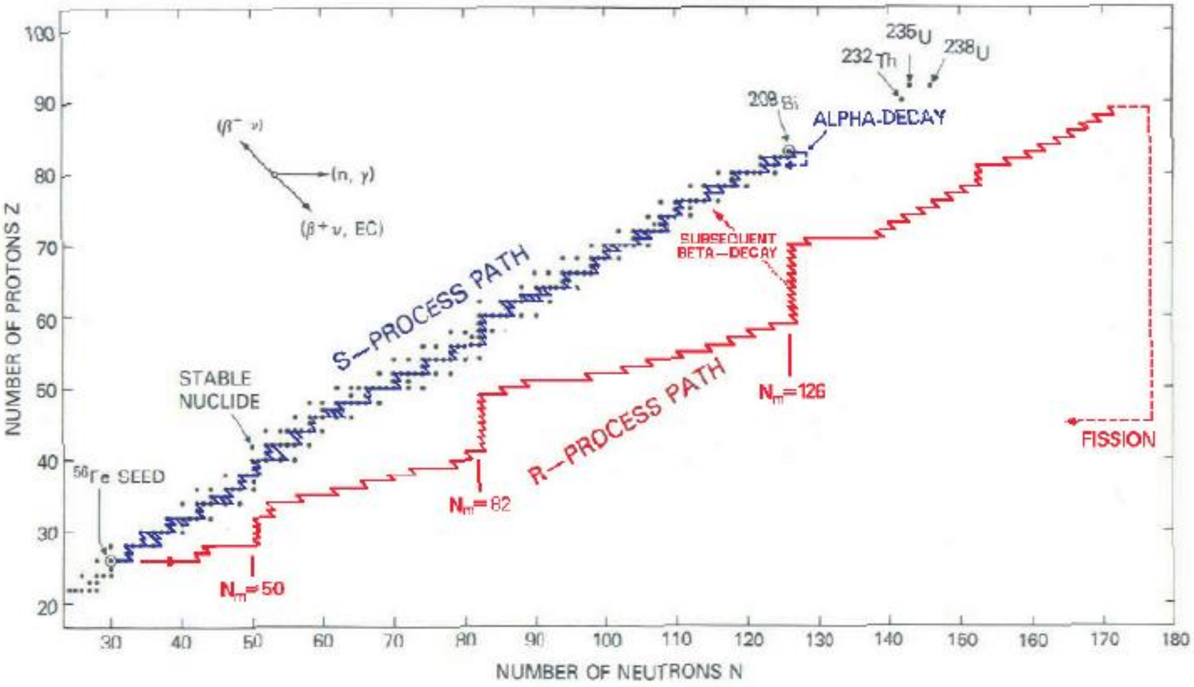
132
s,r
134
r
136
r
r-process path
s-process path



NUMBER OF PROTONS Z
NUMBER OF NEUTRONS N
S–PROCESS PATH
R–PROCESS PATH
STABLE NUCLIDE
56Fe SEED
209Bi
ALPHA-DECAY
232Th
235U
238U
SUBSEQUENT BETA–DECAY
(n, γ)
(β+ν, EC)
Nm=50
Nm=82
Nm=126
FISSION

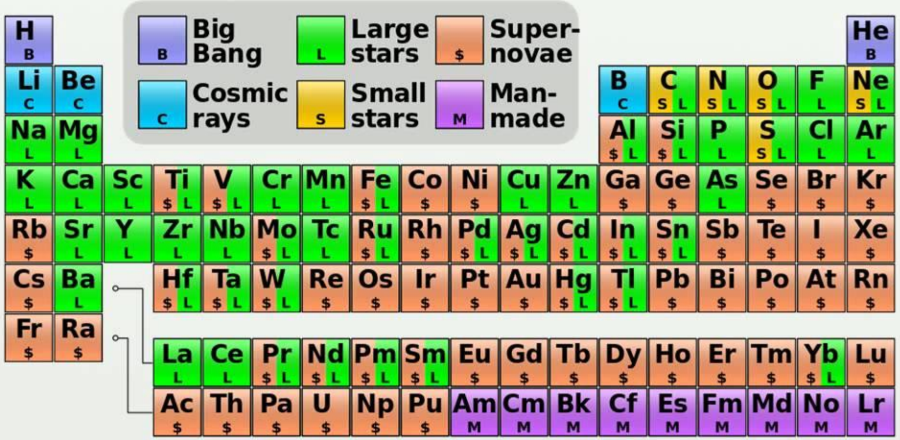
S process

- Main strong s process (from Sr to Pb) in He rich intershell of low mass AGB stars through C13 + He4 gives O16 +n
- Weak s process (from Fe to Sr) in massive AGB near solar metallicity through Ne22 + He4 gives Mg25 + n

The possible sites for r process

- SN explosions
- Merger of neutron stars
- Interaction between a neutron star and a black hole

r-process



https://en.wikipedia.org/wiki/File:Nucleosynthesis_periodic_table.svg

2017

The year of an event observed on the 17^{th} of August both by its electromagnetic and its gravitational waves emissions GW170817

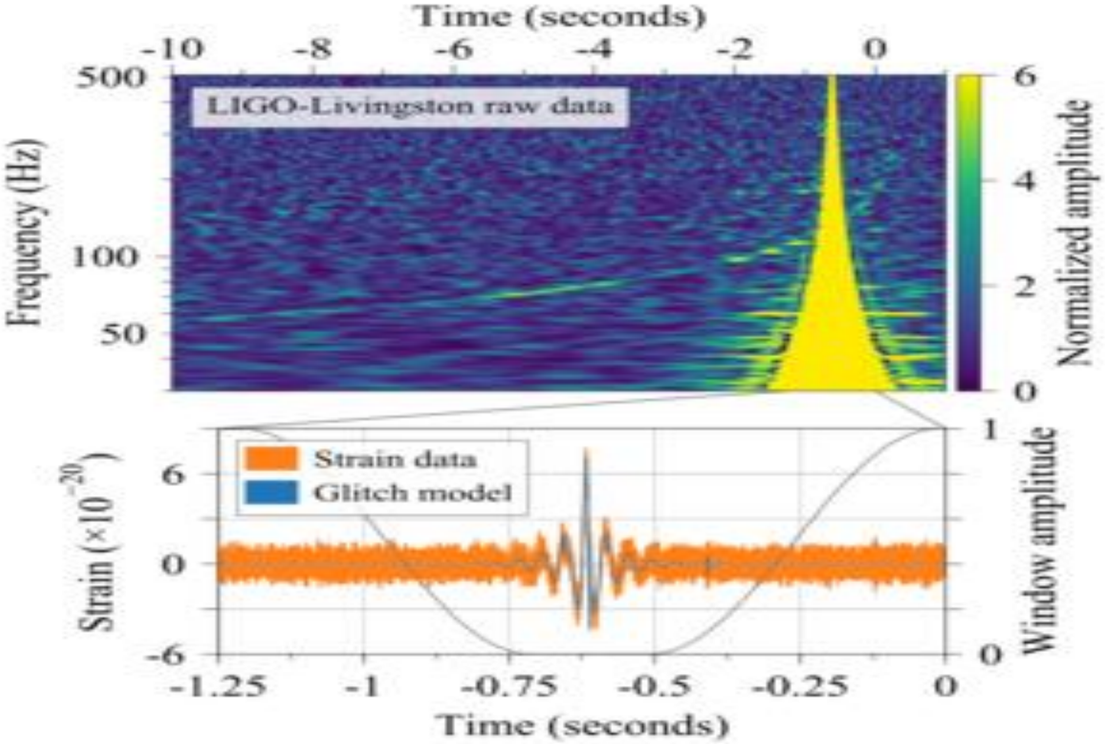
NGC 4993

Lenticular Galaxy in Hydra constellation

Distance of 47,6 + or – 3,4 MPC (155 M l. y.)

Where the 17th August 2017 event took place

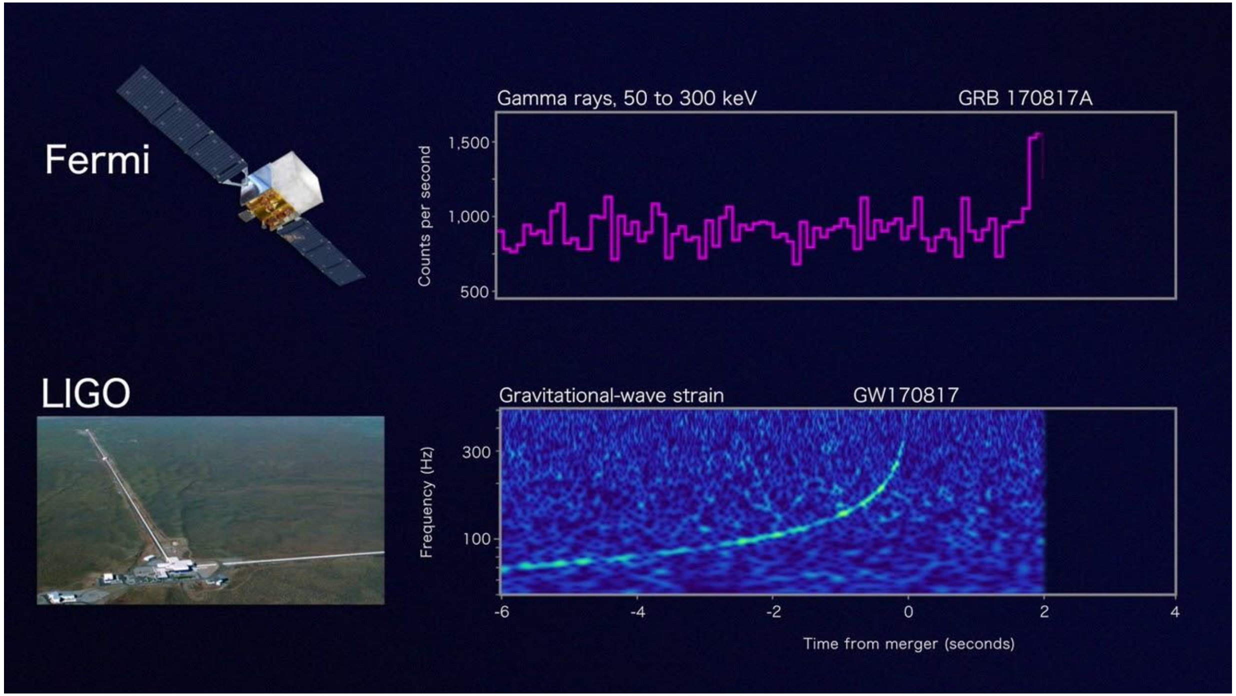
The GW 170817 event



The 170817 GW event

- Occurs at 12H41 UTC for a duration of 100 sec.
- Merging of two neutron stars (1.37 and 1.17 solar mass)
- Resulting neutron star (2.74 solar masses ; R = 11.9 km)
- E = 0.025 solar mass x c2

The related observations of the merging of two neutron stars (GW) and a gamma –ray burst event

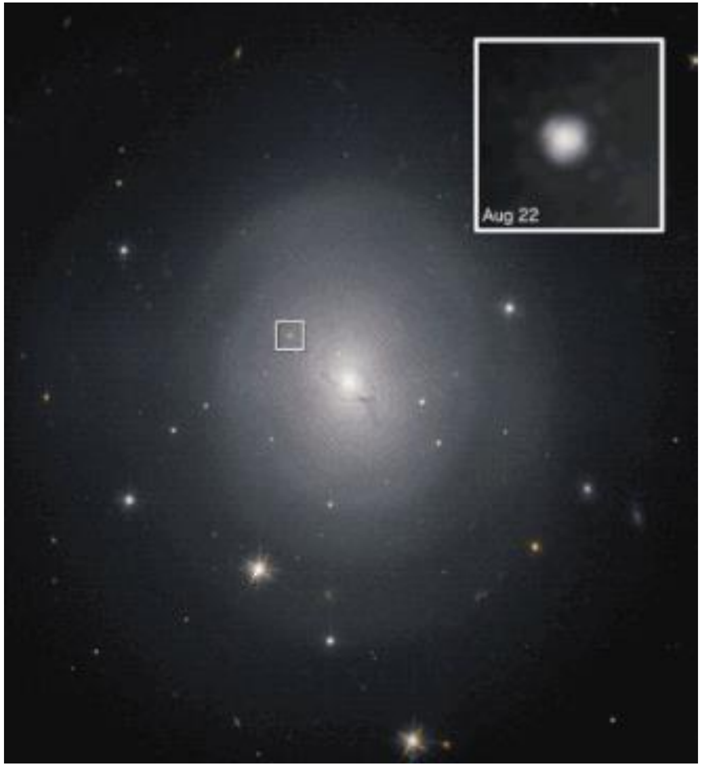


About the related GRB event

Observed by the Fermi satellite 1.74 sec. after GW

Belongs to the less energetic class

The astronomical transient AT2017gfo



This AT2017gfo also called a kilo nova

First detected by the Swope Supernova Survey

10,9 hours after GW

A supernova evolving very rapidly

Strong lines of Sr discovered in its spectrum : claim that NS mergers are the main sources of r process elements

To prove (or not) the role of the NS mergers in the r process

Two types of investigations :

1 – transfer of the electromagnetic energy released by the decay of radioactive r process by – products

2 – « classical » models of chemical evolution of galaxies

Electromagnetic counterpart of NS mergers powered by the radioactive decay of r process nuclei (I)

1 – Metzger et al (2010)

Source of neutron rich ejecta : a) from tidal forces during the merger ; b) outflows from the accretion disk

Determine the radioactive heating by a nuclear reaction network

Model the light curve with a one dimensional Monte-Carlo radiation transfer radiation

Electromagnetic counterpart of NS mergers powered by the radioactive decay of r process nuclei (II)

Ejected mass 0,01 solar mass provides luminosity of 3 x 10 (41) erg/sec

Very rapid luminosity decay (on one day)

Call it a « kilonova » because L = 10 (3) L(nova)

Predict also a short duration GRB

Electromagnetic counterpart of NS mergers powered by the radioactive decay of r process nuclei (III)

S.J. Smartt et al (2017)

Have observed and modelled the rapidly fading transient and the weak short GRB

Explain this electromagnetic counterpart

with M(ejected) = 0.04 solar mass having a velocity of 0.2 c

« Classical » models of chemical evolution of galaxies

C. Kobayashi et al (2020)

H. Y. Shen et al (2021)

I. Dvorkin, F. Daigne, S. Goriely, E. Vangioni & J.Silk (2021)

They developed two types of models, one with no mixing of the ISM and the second (successful) with turbulent mixing of it

The choice of parameters of Dvorkin et al

They follow the evolution of the Eu abundance in NS mergers and NS – BH interaction

They assume Eu mass produced in each merger of 10 -4 solar mass and a SFR efficiency of 0.03 solar mass/year

The limitation of all these models : too many free parameters e.g. the time delay between the formation and the merger of N.S.

Conclusion

Huge potential of observations both « gravitational » and « electromagnetic »

Models of chemical evolution of galaxies and of electromagnetic counterparts of NS mergers seem to indicate that most r process nucleosynthesis occurs in these mergers. But many more multi messenger observations are needed to reach a useful conclusion