Astrophysical compact objects

Part I: Introduction and astrophysical basics

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Outline

1. Introduction

2. Stellar evolution

3. Compact objects
   - White dwarfs
   - Supernovae
   - Neutron stars
   - Binary neutron stars

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Many different stars

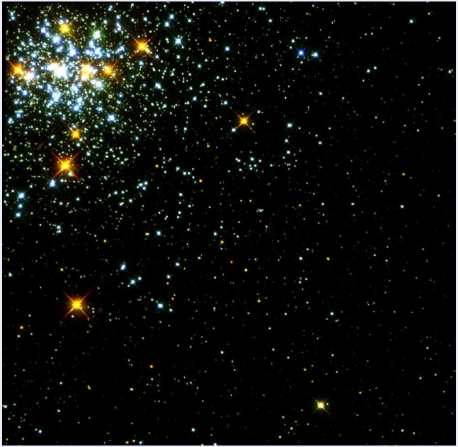
In our Galaxy (Milky Way), there are $\sim$ 200 billion stars

Stellar masses :
$0.2M_\odot < M < 100M_\odot$
(solar mass : $M_\odot = 2 \times 10^{30}$kg)

Stellar (effective temperatures) :
$3 \times 10^3 \lesssim T_{eff} \lesssim 4 \times 10^4$K

How do the different types of stars counterbalance gravity ?

Open cluster NGC 1818 in the Large Magellanic Cloud



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“Normal” stars

Nuclear burning

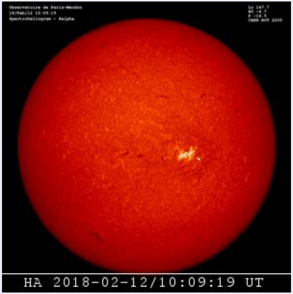
In 1930’s : big progress in understanding nuclear reactions
$\rightarrow$ nuclear burning (fusion) as energy source in stars :
H $\rightarrow$ He (pp chain) [Bethe & Critchfield 1938] ;
CNO cycle [Bethe 1939, von Weizsäcker 1938]

Nobel prize to Hans Bethe 1967

Sun : hydrogen burning

More massive stars : other burning stages

Observation of the Sun, H_α line [Observatoire de Paris]



Hans Bethe

Carl Friedrich von Weizsäcker

Charles Critchfield

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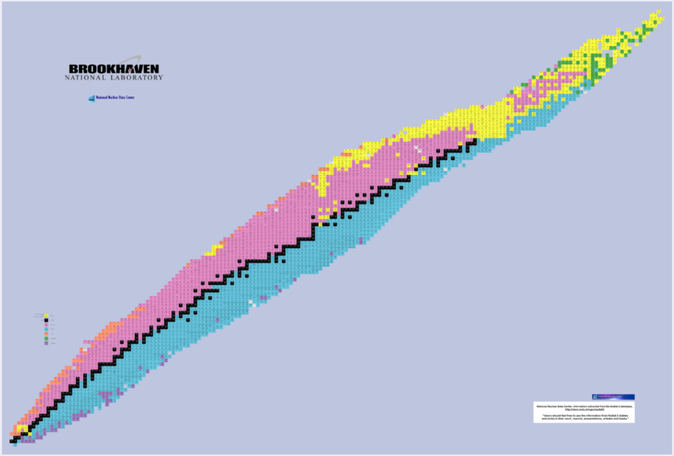
Where do heavy elements come from ?

- Iron has the lowest energy par particle of all nuclei $\longrightarrow$ nuclear fusion no longer energetically favored for producing heavy elements
- But still life on Earth based on many heavy elements !

Table of nuclides [NuDat 2 data]

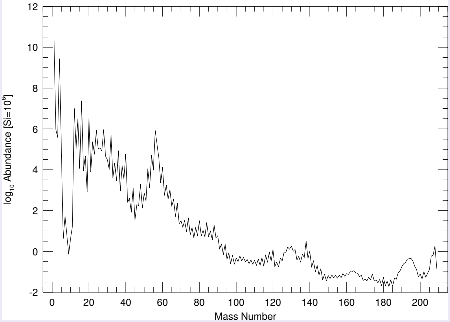


Elemental abundances

- H ($\approx$ 75%) and ^{4}He ($\approx$ 25 %) by far the most abundant baryons known in the Universe

- Different groups of nuclei
  - Light elements up to B (rare)
  - C,N,O, Ne, Mg, Si, iron peak nuclei (much more abundant)
  - Heavy nuclei
- Different sites for the production of these elements (nucleosynthesis)

Solar system abundances [Hix & Thielemann 1999]



Plan

Pre main-sequence phase

For an object to become a star, conditions should be met to activate nuclear reactions

- Gravitational collapse of regions in molecular clouds → protostar is heated
- Further contraction and heating as "T Tauri stars"
- If $T \gtrsim 10^7$K, hydrogen fusion ignited and star enters Main sequence
- High temperature needed to penetrate Coulomb barrier
- Mass at this moment is called "zero age main sequence"(ZAMS) mass
- Formation of massive stars not well understood

NGC 2264, young cluster with many pre main sequence stars [Credit : ESO]

The Main Sequence

The Main Sequence is defined as the stage during which a star burns hydrogen in its core

- Hydrogen burning through two different mechanisms
  - pp-chain
  - Carbon-Nitrogen-Oxygen (CNO) cycle
- Both mechanisms burn 4 protons for a ^{4}He nucleus, energy gained per reaction is roughly 27 MeV
- pp chain and CNO cycle have very different temperature dependence
  - at low T : pp chain dominant (Sun)
  - at high T : CNO dominant (AGB stars, $T \approx 45 - 100 \times 10^6$ K)

  since temperature higher in more massive stars $\longrightarrow$ CNO dominates in more massive stars ($M \gtrsim 1.4 M_\odot$)
- Stellar structure depends a lot on burning mechanism

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What happens if all hydrogen is burned ?

The answer depends strongly on the mass of the star

- Hydrogen first exhausted in the core, still a hydrogen burning outer shell
- At the end of hydrogen burning, core contracts due to gravitation and is heated up
  - The temperature is not sufficient to ignite He-burning
    $\longrightarrow$ red giant $\longrightarrow$ white dwarf
  - The temperature is sufficient to ignite He-burning
- He-burning reaction $3 \times^4 \mathrm{He} \rightarrow^{12} \mathrm{C}$ and possibly $^{12}\mathrm{C} +^4 \mathrm{He} \rightarrow^{16} \mathrm{O}$
- H-burning outer shell remains

- Same story again, depending on ZAMS Carbon burning might be ignited
  - No C-burning $\longrightarrow$ white dwarf
  - C-burning $\longrightarrow$ core-collapse supernova
- Later burning stages have shorter duration

Example for a 25 $M_\odot$ star

burning stage	$T_c(10^6\mathrm{K})$	duration
H	10	$7 \cdot 10^6$y
He	150	$5 \cdot 10^5$y
C	500	600y
Ne	800	1y
O	1200	150d
Si	2000	1d

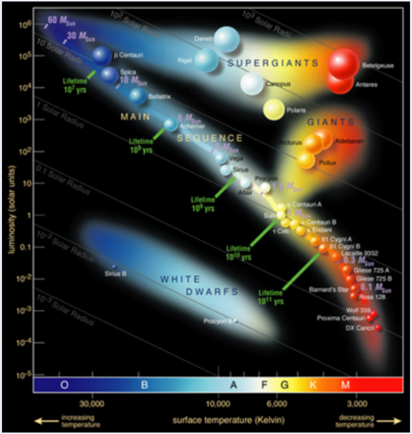
Hertzsprung-Russell diagram

Many different versions, basic idea : the star's effective surface temperature (spectral type) vs luminosity

Identification of different branches

- Main sequence stars
- (horizontal) Giant branches
- Dwarf stars

Indication for different nuclear burning stages and different evolution
(roughly) the more massive the main sequence star

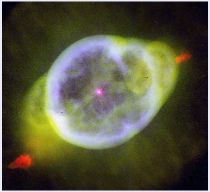


- the higher the temperature and pressure in the core
- the higher the luminosity
- the faster the consumption of nuclear fuel $\longrightarrow$ shorter lifetime

And if no more nuclear fuel is available ?

White dwarf

[NGC 3242, Hubble]

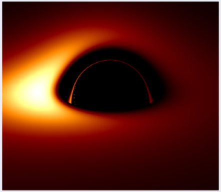


Neutron star

[Crab nebula, Chandra]

Black hole

[GYOTO, Vincent et al 2011]



- Low and intermediate mass stars : He burning core becomes degenerate, temperature not high enough to ignite Carbon burning $\longrightarrow$ expulsion of the envelope, core contracts until forming a white dwarf (electron degeneracy pressure stabilises the star)
- Stars with $M \gtrsim 8 - 10 M_\odot$ at ZAMS continue nuclear burning until reaching iron (lowest energy per nucleon)
  $\longrightarrow$ core-collapse supernova explosion
  $\longrightarrow$formation of a neutron star (stabilised by nuclear forces)
  or a black hole at the center

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Compact celestial bodies

- White dwarfs, neutron stars, and black holes are classified as compact objects because of their small size compared to their mass.
- The gravitational field is extremely intense in their vicinity. In newtonian gravity we can estimate the gravitational energy at the surface as

$$E_{grav} = -G \int_0^R \frac{m(r)}{r} dm = -4\pi \int_0^R m(r)\rho(r) r dr \ .$$

Assuming a constant density this gives $E_{grav} = -\frac{3}{5}\frac{GM^2}{R}$.

The ratio of gravitational and mass energy of the star is then

$$\frac{E_{grav}}{Mc^2} = -\frac{3}{5}\frac{GM}{Rc^2} \ ,$$

which allows to define a *compactness* parameter

$$\Xi = \frac{GM}{Rc^2} \ .$$

	Ξ
Earth	10^{-10}
Sun	10^{-6}
White drwarf	10^{-4}-10^{-3}
Neutron star	~ 0.2
Black hole	1

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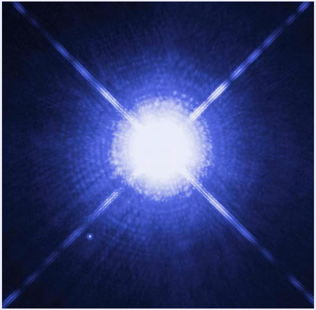
White dwarfs

- Historically,
  - Bessel (1844) : indirect detection of Sirius B from small irregularities n the mouvement of Sirius A
  - Clark (1862) :
    direct observation of Sirius B
  - Sirius B is a star with

$$M = 0.978 \pm 0.005 M_\odot$$
$$R = 0.00864 \pm 0.00012 R_\odot$$

$\longrightarrow$ compact star stabilised by electron degeneracy pressure

Sirius A and B



Hubble Space telescope

- Nowadays $\approx$ 20 000 white dwarf stars observed (SDSS)
  - radii of several thousands of kilometers,
  - most systems have masses $\sim 0.6 M_\odot$, some above $M_\odot$
  - observed surface magnetic fields can reach 10^9G
  - rotation rates $\sim$ tens of seconds to decades

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Chandrasekhar limit

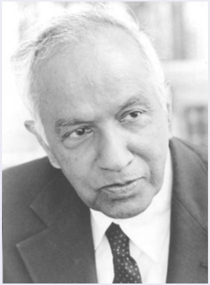
Assumptions :

- Matter pressure given by degenerate electron gas
- Composition enters via charge neutrality
- Gravity described by Newtonian laws

$\longrightarrow$ star can be stabilised only for

$$M \lesssim 1.46(2Y_e)^2 M_\odot$$

Subrahmanyan Chandrasekhar



Known corrections to the Chandrasekhar limit :

- Electrostatic corrections $\longrightarrow$ small reduction of maximum mass
- Finite temperature and slow rotation $\longrightarrow$ no significant change
- General relativity $\longrightarrow$ reduction of maximum mass by $\sim 5\%$

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Supernovae : some historical events

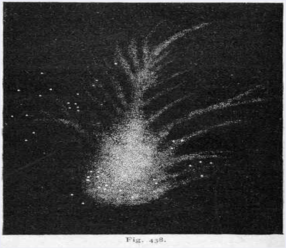
Supernova explosions observed since almost 2000 years
1006, 1054, 1181 : observed by arab/chinese astronomers
1572 : Tycho Brahe
1604 : Johannes Kepler

Tycho Brahe

Johannes Kepler

Observable with the human eye !
Supernova 1054 : « rediscovered »par John Bevis in 1731

Sketch by Lord Rosse, 1844



Remnant is called "Crabe" nebula following the sketch by Lord Rosse

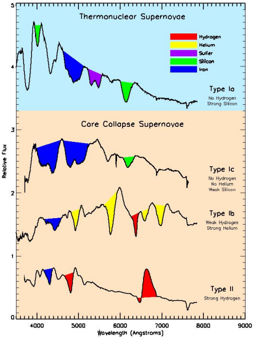
Distance is $\sim$ 6500 light years

Supernovae

Observational classification

- Observational classification following spectral features near peak luminosity

Class	Spectral feature
SN Ia	no H, Si
SN Ib	no H, no Si, He
SN Ic	no H, no Si, no He
SN Ic -BL	as Ic, broad lines
SN II	H
SN IIb	H, Ib at late times
SN IIn	H, narrow lines
SNSN	super-luminous events



[Credit : D. Kasen, LBL]

- Physical origin
  - SN Ia : thermonuclear explosion of a WD
  - All other types : gravitational collapse and subsequent explosion of a massive star

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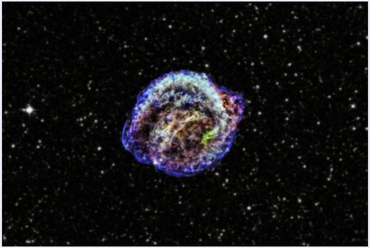
Supernovae : physical mechanisms

I : Thermonuclear explosions

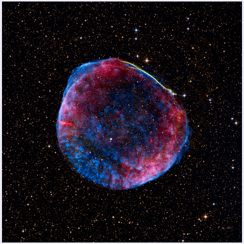
Kepler SN remnant



[Credit : NASA (Chandra)]

- No remnant left behind → nebulae
- Very similar observed lightcurves → standard candles

SN 1006 remnant



[Credit : ESO (combined image)]

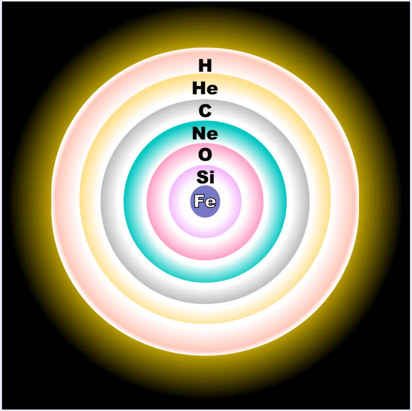
- Type Ia Supernovae : ignition of runaway nuclear fusion in a white dwarf and subsequent explosion
- Majority of observed supernovae
- Different progenitor scenarios possible

Supernovae : physical mechanisms

II : Core collapse supernovae

- Iron core above Chandrasekhar limit : can not sustain its own mass $\rightarrow$ collapse ($t \sim 100$ ms)
- Electron capture reactions during collapse $p + e^- \rightarrow n + \nu_e$ lower pressure
- Bounce if matter at the centre has reached approximately the density of nuclei (nuclear repulsion) $\rightarrow$shock wave propagating outwards
- Detailed explosion mechanism very complicated and not yet fully understood

Onion like structure of a presupernova star [Wikipedia]



- Simple estimate of energy released :

$$\Delta E = E_{\rm grav}(\text{presupernova core}) - E_{\rm grav}(\text{neutron star}) = \Xi M c^2 \approx 10^{46}\,\text{J}$$

Almost the radiation of a whole Galaxy during 30 years !

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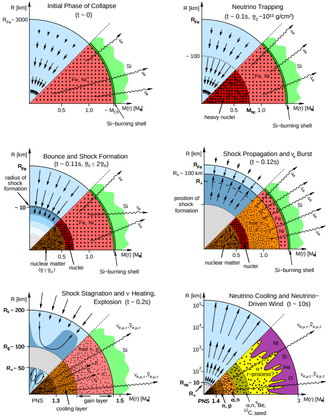
Core collapse supernovae

Neutrino-driven explosions

- Initial collapse phase : compression (+deleptonisation) $\rightarrow$ heavier and more neutron rich nuclei
- Neutrino trapping with homologous collapse
- Shock stalled at ~ 200 km due to interaction with infalling material (photodissociation of nuclei)
- Shock revival via neutrino heating emitted from the central region
- Multi-D hydro instabilities aid the explosion

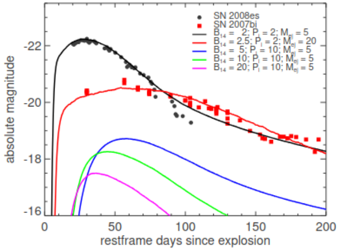


[Janka+ 2007]

Core collapse supernovae

Alternatives for explosion mechanism

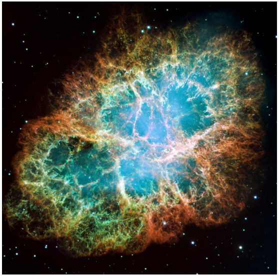
- Magneto-rotational explosions :
  - Very energetic events (total luminosity typically 10-100 $\times$ typical supernova)
  - Indication for strong magnetic field and fast rotation
  - Magnetic fields extract energy from rotation $\longrightarrow$ powerful jet-driven explosions
- Explosion aided by first order (hadron-quark) phase transition



[Kasen&Bildsten 2010]

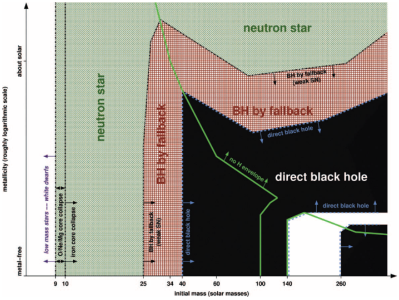
Core collapse supernovae

Outcome



[credit :HST]

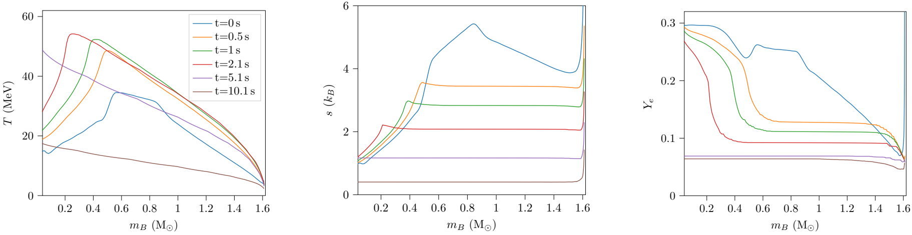
- No simple argument to predict fate :
  - Main factors metallicity and initial mass (ZAMS)
  - Other factors binarity, rotation, magentic field etc



[credit :Heger+2003]

- Supernova remnant : material ejected by explosion
- At the centre : neutron star or stellar black hole

A proto-neutron star



[Pascal+ 2022]

- Almost 99% of the energy of a CCSN taken away by neutrinos
- At bounce, matter at the very center hot and very dense, β-equilibrium reached : $p + e^- \leftrightarrow n + \nu_e$ with trapped neutrinos
- Neutronised matter $Y_p = n_p/n_B \approx 0.3$
- Convective effects lead to flat entropy and composition profiles
- PNS cools down ($t \sim$ minutes) essentially by neutrino emission to form a neutron star or a black hole

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A NEUTRON STAR : A STAR MADE OF NEUTRONS....

- 1932, Landau (Phys. Z. Sowjetunion, 1, 285)
  Possibility of stars with a central density comparable to that of nuclei
- 1934, Baade and Zwicky (Phys. Rev. 45, 138)
  Prediction of the existence of neutron stars : *With all reserve we advance the view that supernovae represent the transition from ordinary stars into neutron stars, which in their final stages consist of extremely closed packed neutrons.*
- 1939, Tolman, Oppenheimer, and Volkov
  General relativistic neutron star models : $M \approx 1.5 M_\odot$ and $r \sim 10$ km $\rightarrow$ density $\sim 0.1\ \mathrm{fm}^{-3}$

WALTER BAADE

FRITZ ZWICKY

No observable signal $\rightarrow$ almost forgotten for about thirty years . . .

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1967, DISCOVERY OF PULSARS

Anthony Hewish and his PhD student Jocelyn Bell study the sky scintillation with radio waves. J. Bell finds a source oscillating with $T = 1.34\ s$.

Shortly after different similar sources are detected including millisecond pulsars $P \ll 1$ s.

The pulse frequency remains almost constant. For example, change of 40 ns per year for the pulsar first discovered by J. Bell.

Pulsar = pulsating source of radio

Pulsars have been identified as rotating neutron stars Pacini& Gold, 1968

Jocelyn Bell did not receive the Nobel prize, only A. Hewish received it in 1974.

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Neutron star or white dwarf ?

Maximal rotating frequency : Kepler frequency (centrifugal force = gravitational force at the equator)

$$R\Omega_K^2 = \frac{GM}{R^2}$$

Mean density :

$$M = \frac{4}{3}\pi R^3 \bar{\rho}$$

Minimal period :

$$P_{min} = \frac{2\pi}{\Omega_K} = \sqrt{\frac{3\pi}{G\bar{\rho}}}$$

$P_{min} \sim 1s$ for white dwarfs with $\bar{\rho} \sim 10^{11}\,\frac{\mathrm{kg}}{\mathrm{m}^3}$

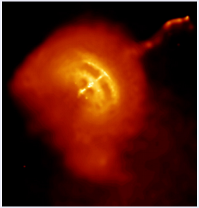
Nowadays

- Almost 3000 neutron stars have been observed as pulsars, among others Crab, Vela, Geminga, Hulse-Taylor double pulsar, ...

Crab pulsar

Hubble (blue, optic), Chandra (red, X)

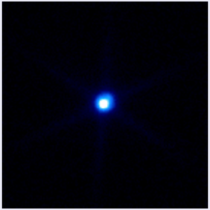
Vela pulsar



Chandra (X)

- Some ("the magnificant seven") have been observed only by their thermal emission
- "Magnetars" have extremely high magnetic fields ($\sim 10^{15}$ G at the surface)

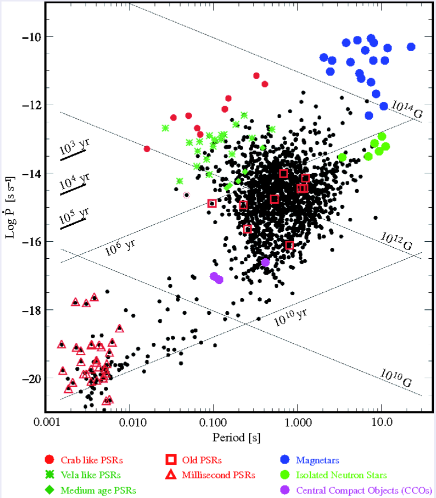
RX J 1856-37



Nowadays

- Almost 3000 neutron stars have been observed as pulsars, among others Crab, Vela, Geminga, Hulse-Taylor double pulsar, . . .
- Pulsars in many different systems
- "Magnetars" have extremely high magnetic fields ($\sim 10^{15}$ G at the surface)

P-$\dot{P}$ diagram

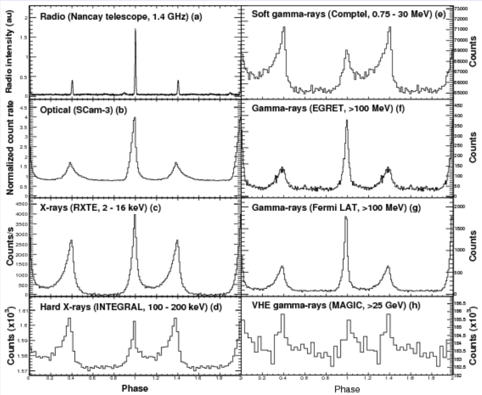


[Becker et al., 1305.4842]

Nowadays

- Almost 3000 neutron stars have been observed as pulsars, among others Crab, Vela, Geminga, Hulse-Taylor double pulsar, . . .
- Pulsars in different wavelengths : information on magnetosphere from pulse profile
- "Magnetars" have extremely high magnetic fields ($\sim 10^{15}$ G at the surface)

Crab pulsar observed in many wavelengths



[Abdo et al, 0911.2412]

Why a “neutron” star ?

Theoretical argument : high density electrically neutral matter in β-equilibrium $\rightarrow$ high neutron fraction

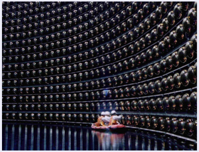
Observational argument : Neutron stars are formed in supernova events. For SN1987A 24 antineutrinos have been observed,

- 11 Kamiokande-II
- 8 IMB
- 5 Baksan

This is generally interpreted as a proof for the classical scenario with two main sources of (anti-)neutrino production, the neutronization reaction $p + e^- \rightarrow n + \nu_e$ and the inverse process $n + e^+ \rightarrow p + \bar{\nu}_e$

SN1987A

Superkamiokande



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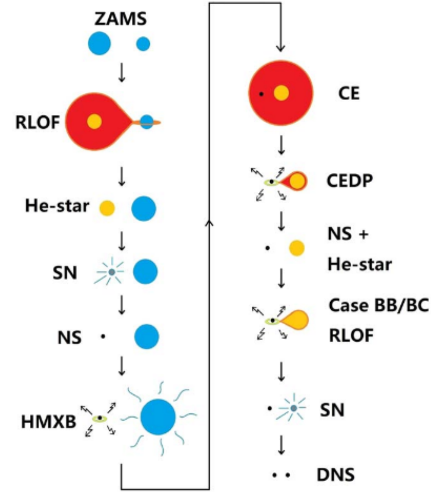
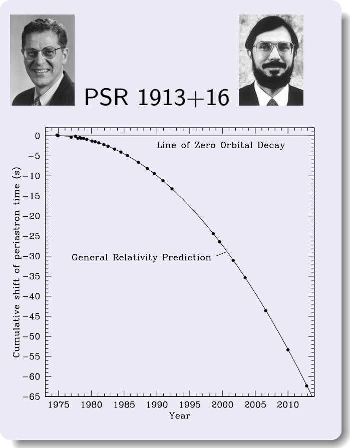


- Majority of stars do not evolve isolated
- Standard formation scenario for a BNS via stellar evolution
- Other possibilities are dynamical captures in dense environments

Binary neutron stars



- First system observed in 1974 by Hulse and Taylor, nowadays $\sim$ 20 known systems in the Galaxy
- Extremely relativistic $\rightarrow$ precise observations allow for testing general relativity and determining neutron star masses
- Good source of gravitational waves $\rightarrow$ change in orbital motion via gravitational wave emission : first (indirect) evidence for gravitational waves (Nobel prize for Hulse and Taylor 1993)

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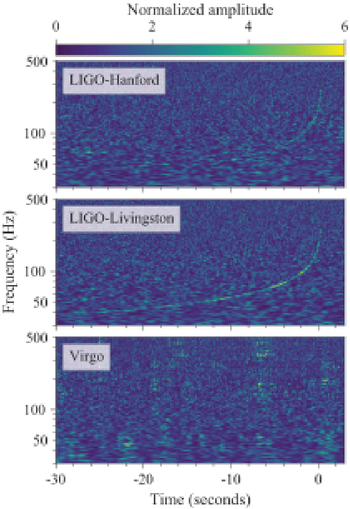
Binary neutron stars

GW detections

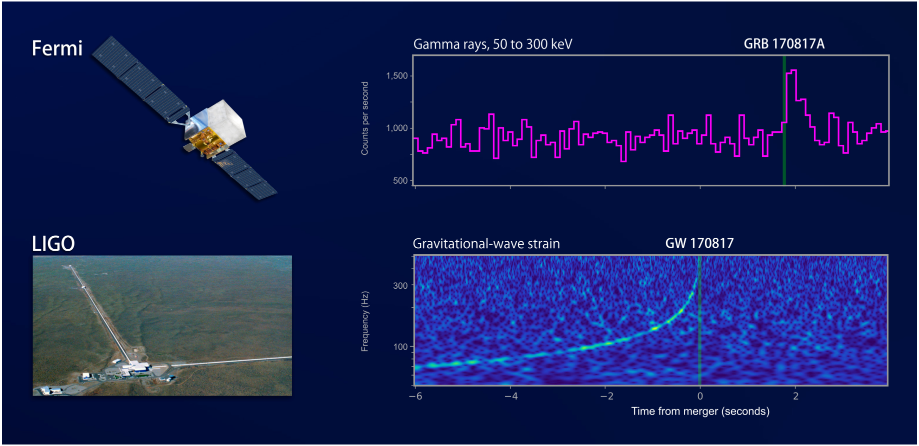


August 17, 2017 : first detection of the coalescence of binary neutron star in gravitational waves

- total mass $2.74^{+0.04}_{-0.01} M_{\odot}$
- distance ~ 40 Mpc
- localisation in the galaxy NGC4993
- GW200105 and GW200115 : first detection of two BH-NS merger events

The event GRB170817A

A short γ-ray burst



Coalescence of two neutron stars $\rightarrow$ formation of a black hole and an accretion disk $\rightarrow$ relativistic jet $\rightarrow$ particle acceleration and γ-ray emission

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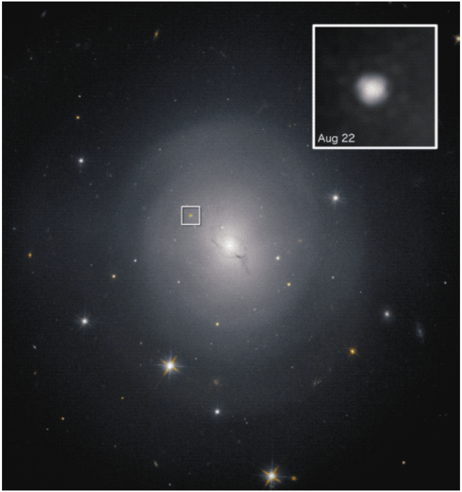
The follow-up of GW170817

A transient source in NGC4993



Observation (electromagnetic) of this source by several telescopes in different wave lengths (γ, X-rays, UV, visible, infrared and radio)

The radiation has becomes less intense and less energetic with time

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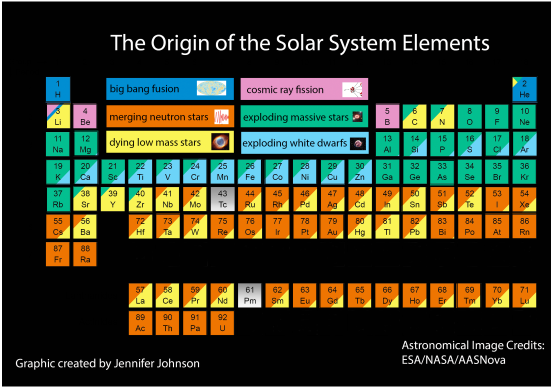
Where do heavy elements come from ?

This radiation, called ≪ kilonova ≫, has its origin in the radioactive decay of heavy nuclei produced in the ejecta of the binary neutron star coalescence :



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