Supernovas
and
the expansion of the Universe

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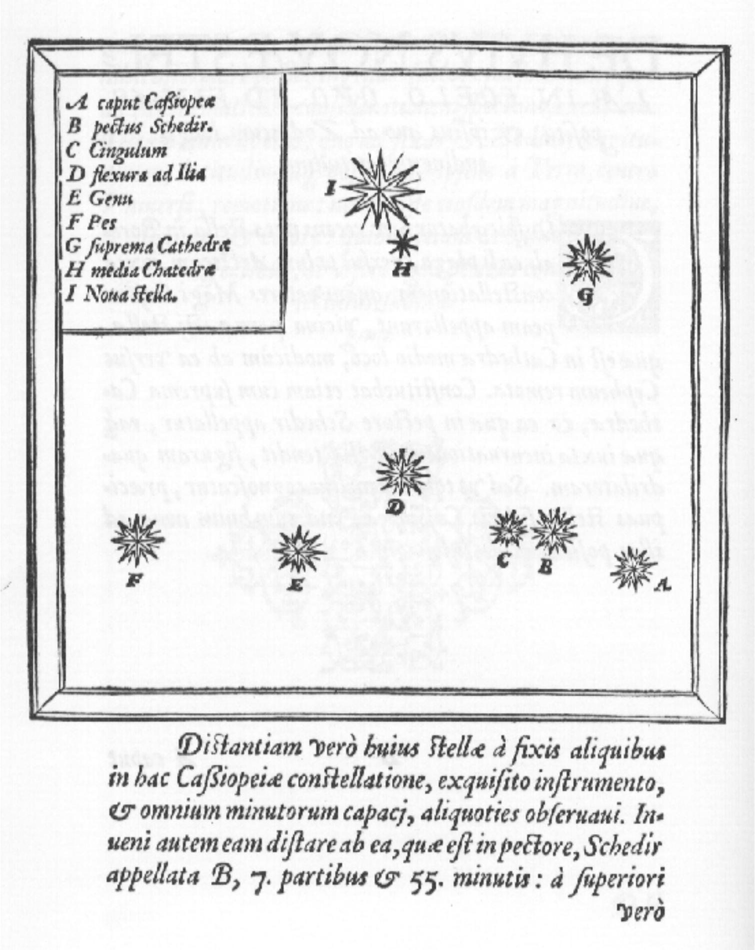
Supernova

- A supernova is a huge explosion of a star.
- The brightness ~10 billion suns ~ the brightness of a galaxy.
- The total energy output ~ 10^{44} J ~ the total energy output of the sun during its 10 billion year lifetime.



A caput Caſsiopeæ
B pectus Schedir.
C Cingulum
D flexura ad Ilia
E Genu
F Pes
G ſuprema Cathedræ
H media Chatedræ
I Noua ſtella.

Diſtantiam verò huius ſtellæ à fixis aliquibus in hac Caſsiopeiæ conſtellatione, exquiſito inſtrumento, & omnium minutorum capacj, aliquoties obſeruaui. Inueni autem eam diſtare ab ea, quæ eſt in pectore, Schedir appellata B, 7. partibus & 55. minutis: à ſuperiori verò

11 novembre 1572

«One night, looking at the sky, as usual, I noticed with great surprise a star with an extraordinary brightness in the constellation of Cassiopeia, not far from zenith. I could not believe my eyes. To be sure, I asked my six lab workers and also passers-by to look at the new star.» - Tycho Brahé

"Luck doesn't exist. What we call luck is attention to detail" –

Winston Churchill

Tycho Brahé
« De Nova Stella»

Nova (plural *novae*) means "new" in Latin, referring to what appears to be a new star, shining in the celestial sphere.

History and Documents

The three «host-stars» of Middle Ages: 1006, 1054, 1181

9 October 1604: Kepler (Lucky?!) observes another «nova stella» in Ophiuchus constellation.

1885: Another nova discovered in Andromeda nebula (galaxy)

The beginning of XXth century:

1930: A systematic research program by Fritz Zwicky of Mont Wilson observatory.

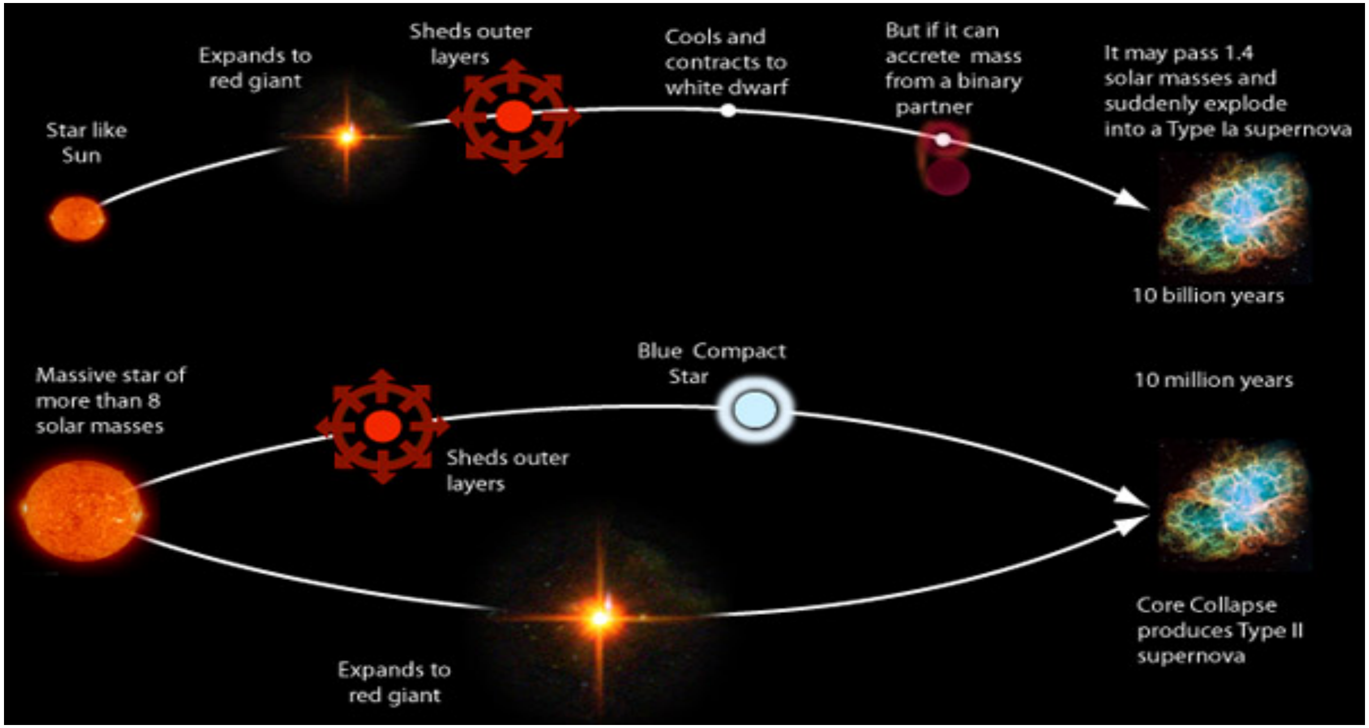
1931: The name supernova given by Zwicky.

The beginning of XXth century

Few hundred supernovas per year.

Estimate that 2-3 supernovas occur each century in a galaxy like Milky Way.

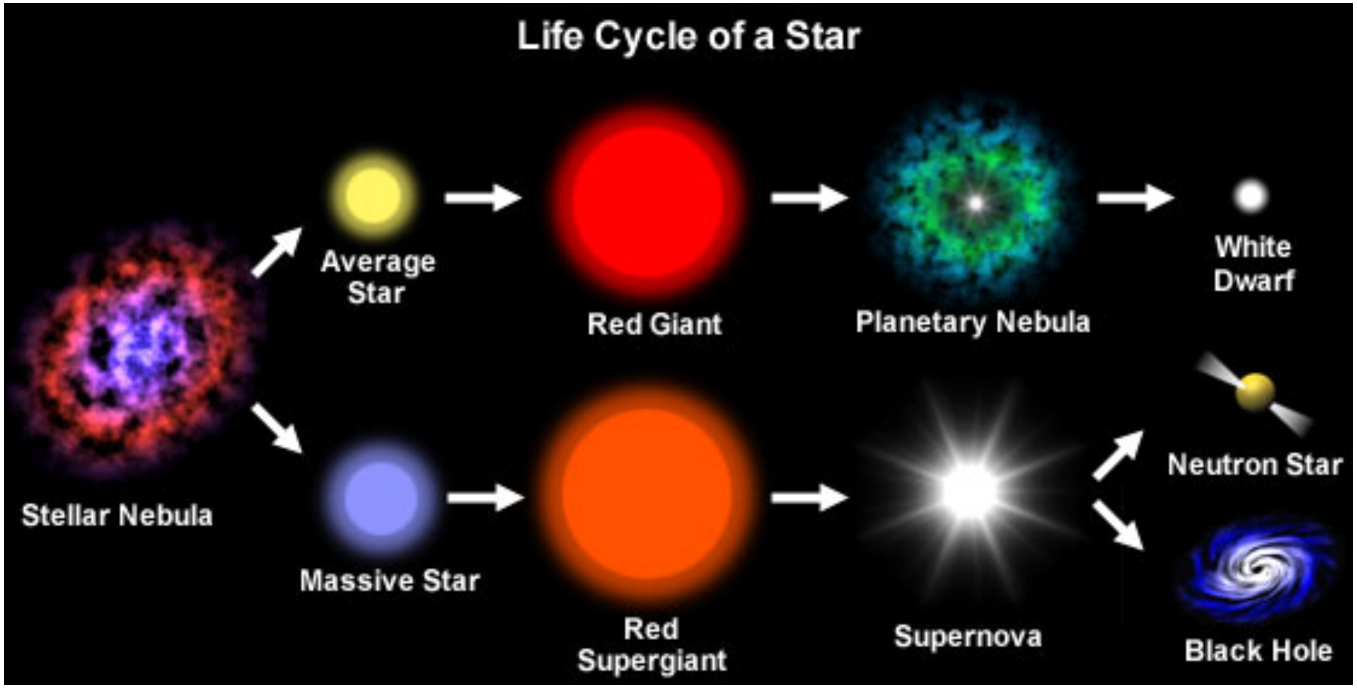
How? Two ways:



Ia: A white dwarf may accumulate material from a stellar companion and burns-up at once.

Others: At the end of its life, a very massive star undergoes a self-explosion.

Stellar evolution



Two branches: below or above 8 solar masses.

Main sequence: Hydrogen to helium. Enough pressure to maintain hydrostatic equilibrium against gravity. The major part of their life.

Red giant: Helium to heavier nuclei. Depending on the star mass, all the elements lighter than iron are produced: C, O, Si, Ca, S, ⋯

Depending on mass, the last remnant is a white dwarf, a neutron star or a black hole, after an explosion.

In case of massive stars, this explosion is a supernova (second type).

Two ways of supernovas

Ia: A white dwarf may accumulate sufficient material from a stellar companion to exceed a limit of 1.4 solar masses.

It burns-up at once in a thermonuclear (carbon fusion) detonation.

Others: After several nuclear fusions – a core of iron is created. No more energy from nuclear fusions.

With a further gravitational collapse - electrons and protons fuse into neutrons - sending out huge numbers of neutrinos.

The shock wave carries the matter with it in a cataclysmic explosion.

Two well - known supernovas

1054 supernova M1 (host star)

Crab nebula supernova remnant;

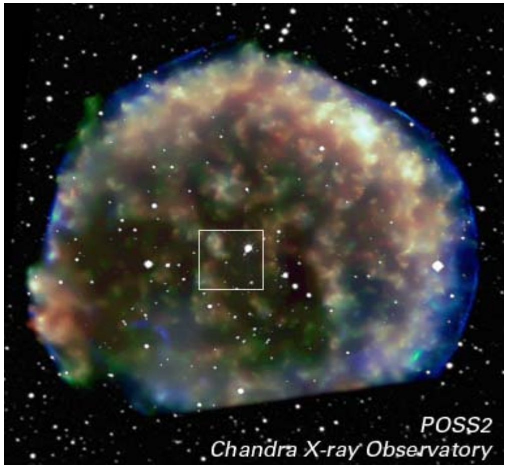
Expanding nebula, 1,500 km/s

6,500 light years away.

A pulsar (neutron star) at the center.

Type II supernova

1572 Tycho supernova (nova stella)



Tycho supernova remnant - debris of a white dwarf;

Expanding nebula, 5,000km/s

8,500 light years away;

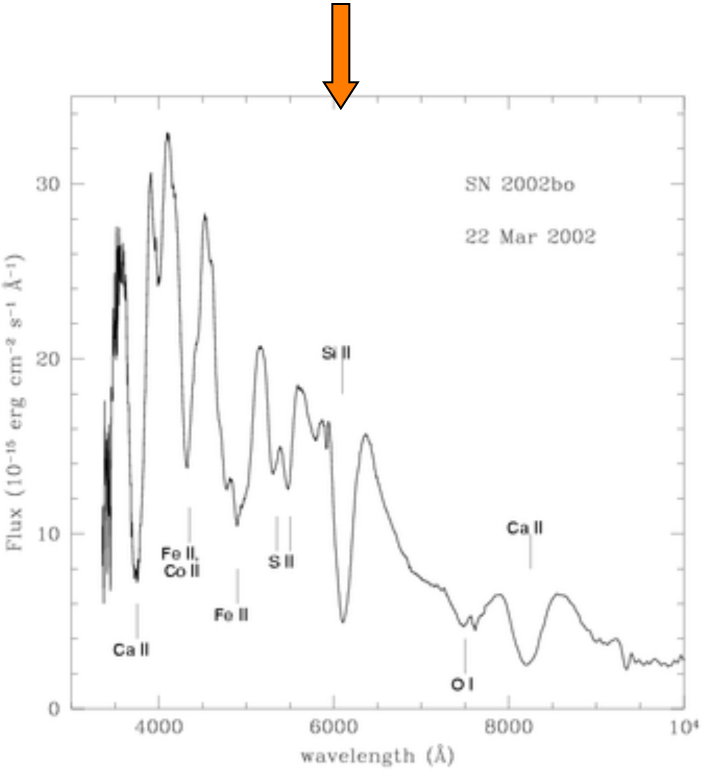
Type Ia supernova

Kepler supernova is also a type Ia.

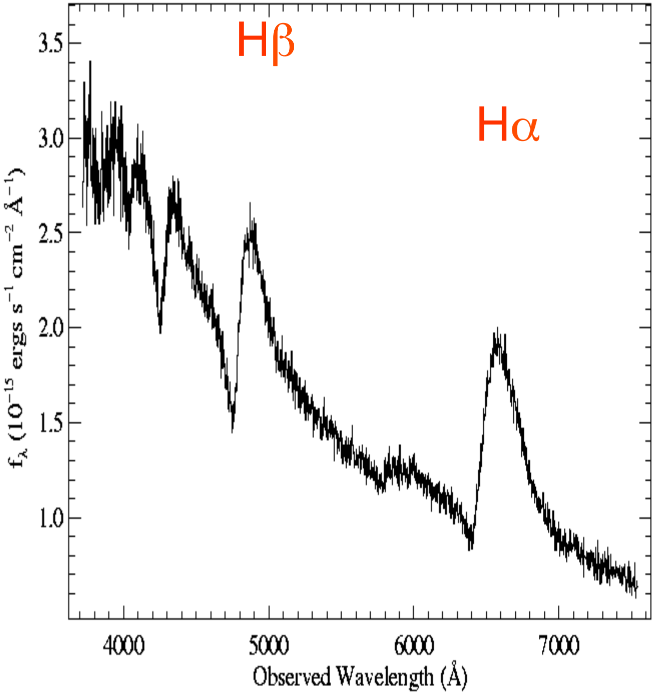
Two ways - Two classes of spectra

type Ia: no hydrogen lines

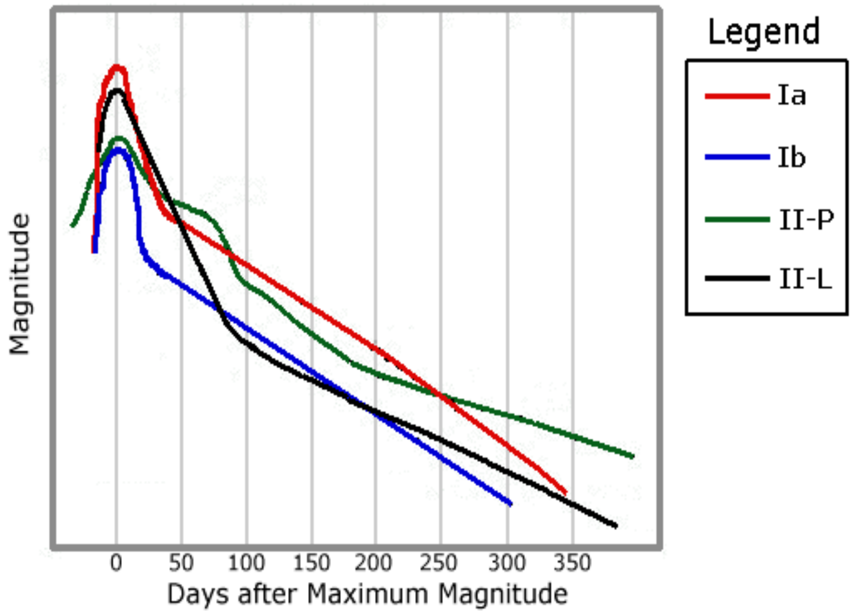
strong silicon line at 6150 Å



type II: strong hydrogen lines



Light curves



Light curves for different types of supernovas

Ia: Light curves with sharp maxima, then dying away gradually.

The maxima may be at about 10 billion solar luminosities.

II: Less sharp peaks at maxima.

The maxima may be at about 1 billion solar luminosities.

Supernovas: released energy

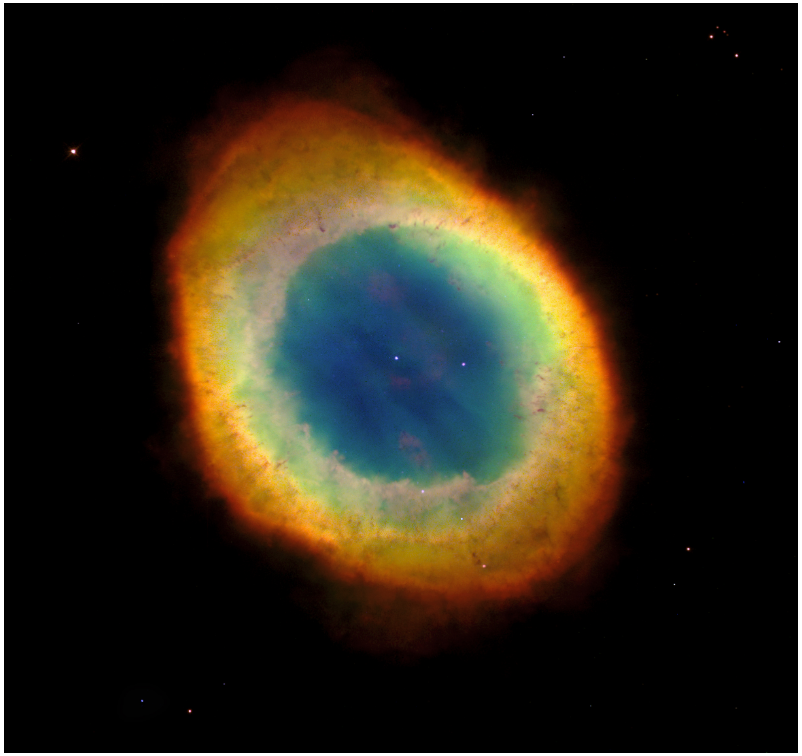
- Typical energy of supernova is 10^{44}J or 10^{51} erg: Fifty-one erg, FOE.
- 1 FOE concerns only the observed energy: electromagnetic energy 1% (brightness like ten billion suns during several days) and kinetic energy of outgoing layers 99%.
- In type II supernovas, about 100 FOE is released by neutrinos, which are invisible to optical observations and hardly observable.
- The flux of neutrinos reaches about 400 FOE per sec, during few seconds. This energy/s is about 4% of the flux (electromagnetic) of the entire universe!!!

Supernovas: astroparticles

- Nebula (supernova remnant) is a high energy plasma of particles, moving with a high speed, of several thousands of km/s;
- Supernova remnants are the main source of heavy elements (created during the lifetime of the initial star).
- They create filaments of material emitting gamma-ray photons with energies up to 10^{14} eV and accelerate electrons and atomic nuclei up to 10^{15} eV.
- Electrons inside plasma, through synchrotron process produce photons of a long-range spectrum up to X rays.

SN Ia and white dwarfs

White Dwarf: the final evolution stage of a star smaller than 8 solar masses.



The Ring Nebula (M57), a envelope of ionized gas, expelled (about 1,600 years ago) by a low mass star at the end of its life.

Is situated 2,300 light years away.

Nebula expending with a speed of 20-30 km/s.

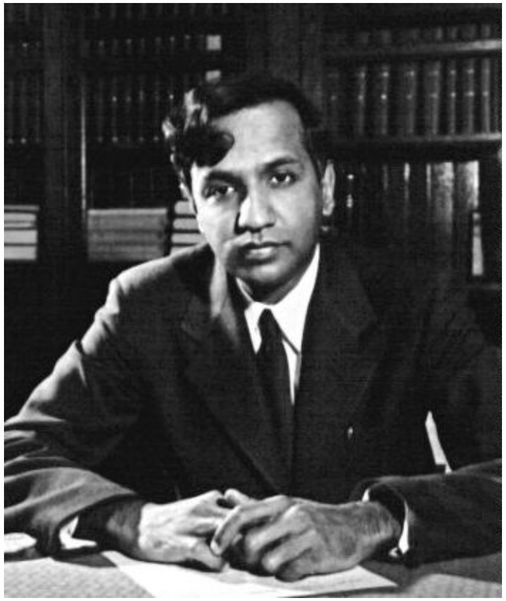
A white dwarf at the center.

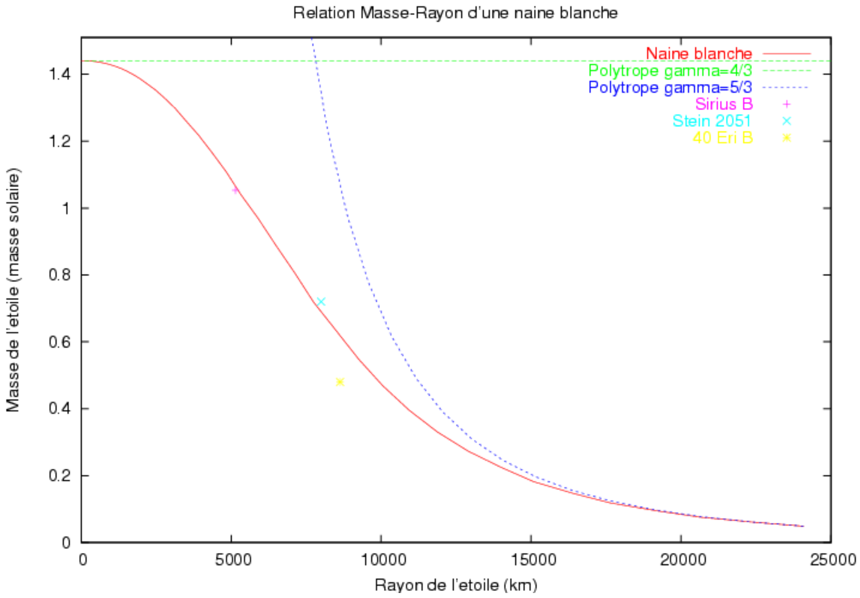
The interior of a white dwarf is a very compact plasma (1 tone per cm^3), composed by a carbon-oxygen mixing.

The electrons are degenerated and constitute a quantum gas.

Quantum gas of electrons

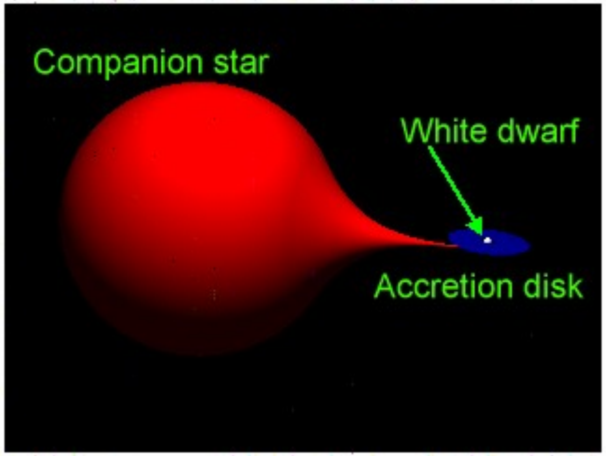
Chandrasekhar (1926) described properties of a star, supported by the pressure of degenerated electrons.





When $M \to M_{Ch} \approx 1.4\ M_o$, $R \to 0$, Chandrasekhar Limit M_{Ch}

Supernova Explosion

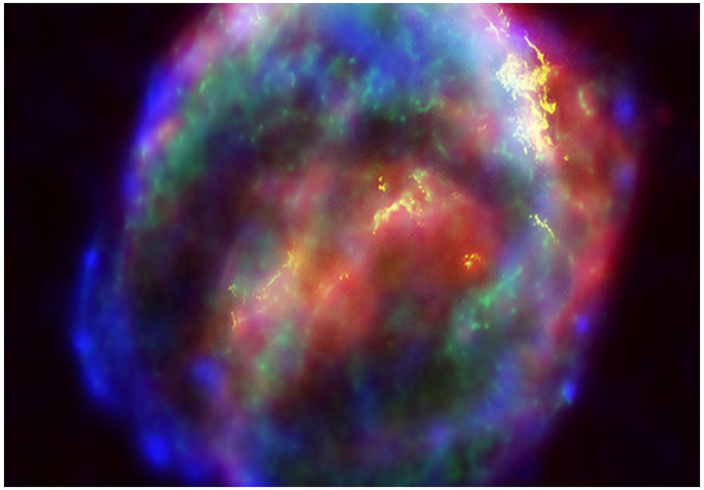


An isolated WD is stable;

But a WD in accretion can approach to M_{Ch}

→ ρ and T increase

→ explosive ignition of C and O



Remains of Kepler supernova.

Production of Si… until Ni

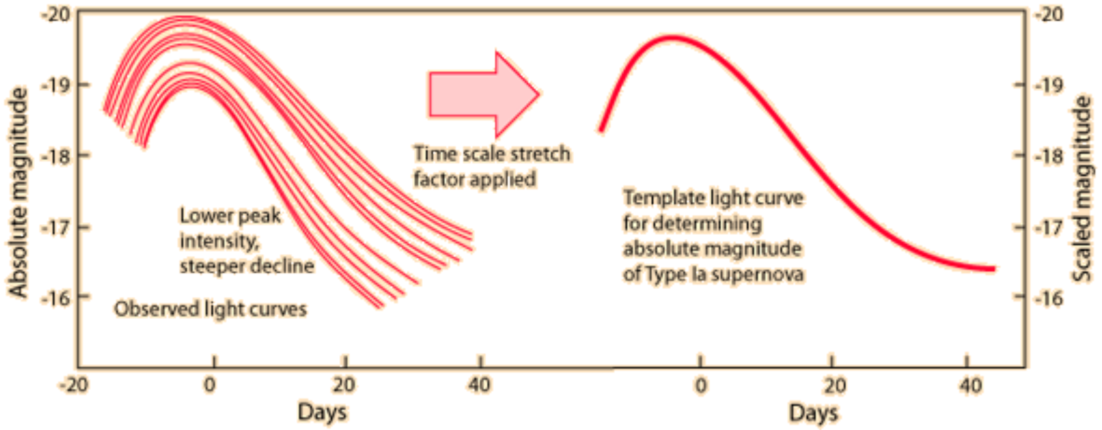
Beta decay till Fe

$^{56}Ni_{28}$ (10 d) → $^{56}Co_{27}$ (111 d) → $^{56}Fe_{26}$

Standardized light curves for SNe Ia

- Type Ia supernova happens when the mass passes the Chandrasekhar limit - all start at essentially the same mass.
- The energy output of the resulting detonation would always be the same - not so simple, but they seem to have light curves closely related.
- It is found that at maximum light, they reach an average maximum magnitude in the blue and visible wavelength bands of -19.3, with a typical spread of less than about 0.3 magnitudes.
- Their light curves vary in a systematic way: the peak brightness and their rate of decay are inversely proportional.

Template light curve



- The "stretch method" - the curves are stretched or compressed in time.
- With such a stretch, all the observed curves on the left converge to the template curve on the right, with very little scatter.
- The peak magnitude M (intrinsic) can be determined by the stretch factor.
- Intrinsic luminosity determined.

Standard candles

$$F = \frac{L}{4\pi D^2} \quad \text{et} \quad m = -2.5 \, Log F + C$$

$$= 5 \, Log D + M$$

F energy flux
D distance
m magnitude (observable)
M absolute (intrinsic) magnitude

- Distance uncertainties for type Ia supernovas are thought to approach 5% .

- (Very) good standard candles!

  - **A similar principal guides for using cepheids-variable stars as standard candles.**

  - **They are characterized by a relation between their period of variability and intrinsic magnitude.**

Hubble Law

At the time and place that Zwicky was watching supernovas…
…Hubble was discovering the Universe expansion.

1929, Hubble uses cepheid stars to measure the distances to the nearest galaxies.

He obtains that galaxies are moving away with a speed proportional to their distance from us.

Hubble Law:

$$V_{exp} = cz = HD$$

z, redshift of the galaxy.

H, Hubble's constant.

Hubble’s Diagram

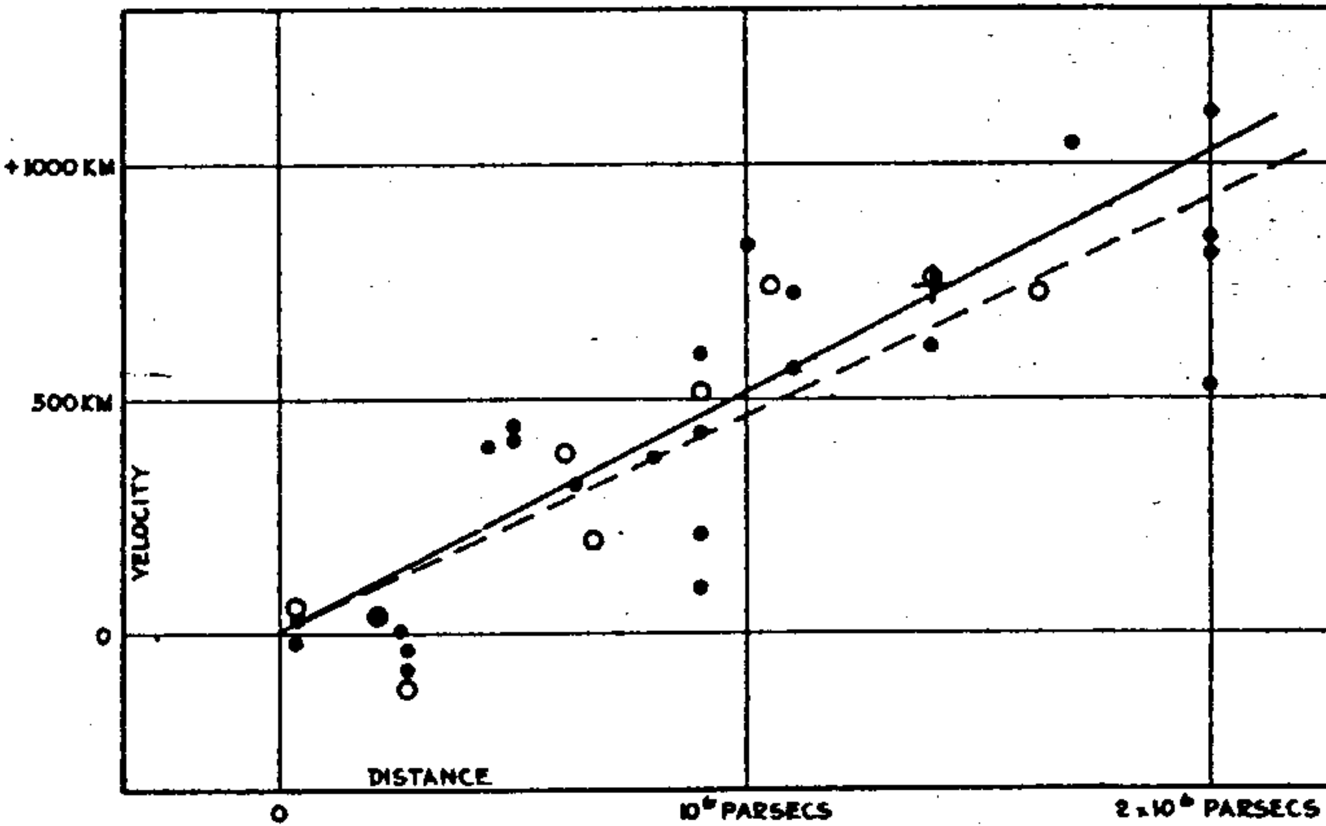


FIGURE 1

H ≈ 70 km/s/Mpc

Big-Bang model of Universe

1916: Einstein GR - no Universe expansion - cosmological constant λ

1922: Friedmann-Lemaître Cosmology: with expansion; decelerating Universe

$a(t)$: scale factor, $1 + z = a(t_0)/a(t)$, $H = \mathring{a}(t_0)\ )/a(t_0)$;

$a = a(t, \rho/\rho_c)$; $\Omega=\rho/\rho_c$;

ρ_c : critical density$=3H^2\ /8\pi G=9.47\text{x}10^{-27}\text{kg/m}^3$

$\Omega = 1$ → Euclidian Universe; infinite expansion

$\Omega < 1$ → hyperboloid open Universe; infinite expansion-ice end.

$\Omega > 1$ → spherical closed Universe; finite time expansion pursued by a Big Crunch-fire end.

Nowadays Observations - (Planck, WMAP...) CMB

The mass density at the current time was assessed to be $\Omega_{m0} = 0.32$.

$\Omega_{m,0}$

Ordinary or baryonic matter is only 0.05, so baryonic matter, constitutes only 17% of the matter of the universe: 1 hydrogen atom per 4 cubic meters of space.

$\Omega_{rel,0}$

The remainder (0.27) is classified as dark matter.

The equivalent mass density of the relativistic particles, made up of electromagnetic energy and neutrinos, is assessed to be $\Omega_{rel0} = 8.24 \times 10^{-5}$.

The matter is strongly dominant over radiation in the current era.

AND

The sum of the contributions to the total density parameter Ω_0 at the current time is $\Omega_0 = 1 \pm 0.004$.

Universe is very close to critical density or $\Omega = 1$.

The mysterious remainder is called **dark energy**,

$\Omega_{\lambda 0} = 0.68$.

$\Omega_{\Lambda,0}$

Similar to the Einstein’s component λ.

The history since the Big Bang is viewed as being at first radiation dominated, then matter dominated, and now having passed into the era where dark energy is the dominant influence.

Supernovas and cosmology: D(z)

,

- Fritz Zwicky: First use of Supernovas to Measure Distances

Charlie Kowal 1968,
till $z=0.005$, D up to 60-70 Mly

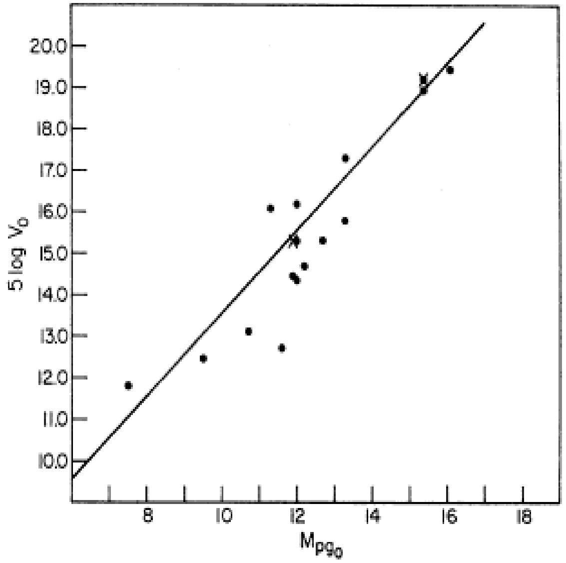
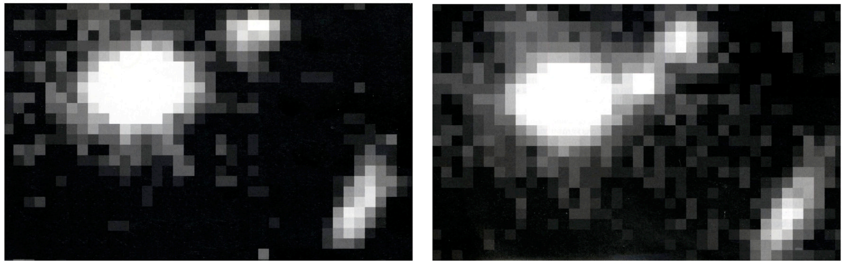


FIG. 1. The redshift–magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.

But for high z (> 0.5)

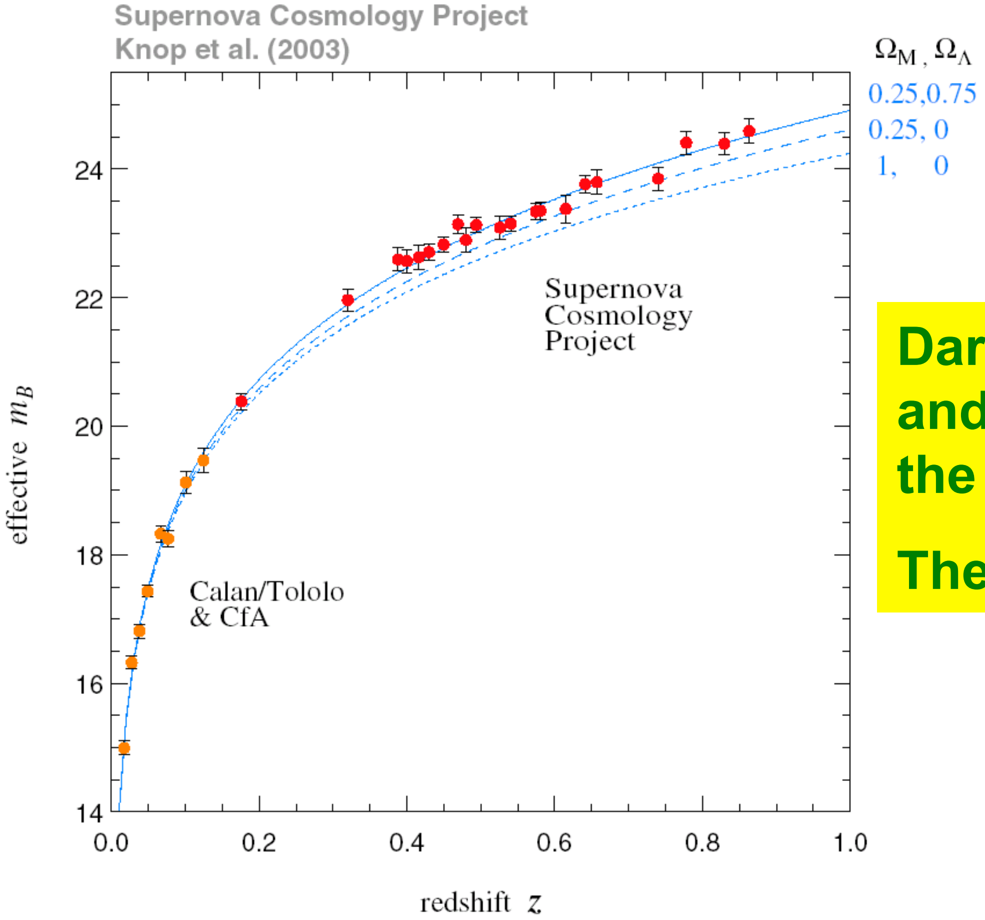
New technology



They proceeded by scanning a piece of sky larger than the size of the moon every 5 minutes to a faintness level, which allows to find Type Ia supernovas halfway across the Universe (z=1).

- Supernova 1995ar. Two images of the same small piece of sky taken three weeks apart were compared. Then, on the second image, a small dot of light was discovered!
- Its status as a type Ia supernova was established after further observations of its light curve.

2003 Hubble diagram for SN Ia


Supernova Cosmology Project
Knop et al. (2003)

$\Omega_M = 1$ is excluded

Dark energy, other than matter and relativistic energy, dominates the Universe.

The Universe is accelerating.

Nobelist-2011: two teams

Supernova Cosmology Project (1988) - 31 members from 7 countries
High z Supernova Search Team (1994) - 20 members from 4 countries

The two research teams raced each other to map the Universe by finding the most distant supernovas.

1998: Accelerating Universe

Perlmutter, Schmidt and Riess

Prize motivation:

“For the discovery of the accelerating expansion of the Universe through observations of distant supernovas"

Challenges of chasing supernovas

- The right kind of supernova has to be found.
- Its redshift and brightness has to be measured.
- The light curve has to be analyzed over time in order to be able to compare it to other supernovas of the same type at known distances.
- This requires a network of scientists that could decide quickly whether a particular star was a worthy candidate for observation. They need to be able to switch between telescopes and have observation time at a telescope granted without delay, a procedure that usually takes months.
- They need to act fast because a supernova fades quickly.

So, once more:

$$\Omega = \Omega_m + \Omega_{rel} + \Omega_\Lambda$$

Total density parameter

$$\Omega = \frac{\rho}{\rho_c}$$

$\Omega = 1$ for critical density universe

Mass density including ordinary mass (baryonic mass) plus dark matter.

Effective mass density of relativistic particles (light plus neutrinos).

Effective mass density of the dark energy, taking the role described as the cosmological constant.

The coming and going of the cosmological constant

- In 1916, Albert Einstein published his General Theory of Relativity, the foundation of our understanding of the Universe. The theory describes a Universe that has to either shrink or expand.
- This disturbing conclusion was reached about a decade before the discovery of the ever-fleeing galaxies. In order to stop this unwanted cosmic expansion, Einstein added a constant to his equations, that he called *the cosmological constant*. Later, Einstein would consider the insertion of the cosmological constant a big mistake.
- With the observations made in 1997–1998, we can conclude that Einstein's cosmological constant – put in for the wrong reasons – was actually brilliant.

From here to eternity

The dark energy is a challenge for physics. Several candidates:

- Einstein's cosmological constant, which does not change over time. So dark energy becomes dominant when matter gets diluted due to expansion of the Universe. The reason for why the cosmological constant entered the scene late in the history of the Universe, only five to six billion years ago. Until then, the expansion of the Universe had been decelerating. With this candidate, the fate of the Universe-eternal expansion!
- The cosmological constant could have its source in the physical vacuum. The simplest estimation for the amount of dark energy does not correspond to the amount that measured actually! An unexplained gap between theory and observation.
- The dark energy is not constant: quintessence, after the Greek name for the fifth element. Quintessence could speed up the Universe, but only sometimes. That would make it impossible to foresee the fate of the Universe.
- To new physics?