The Evolution of Binary-Star Systems

If the stars in a binary-star system are relatively widely separated, their evolution proceeds much as it would have if they were not companions...

If they are closer, it is possible for material to transfer from one star to another, leading to unusual evolutionary paths!
The Evolution of Binary-Star Systems

Each star is surrounded by its own Roche lobe; particles inside each lobe belong to that lobe’s star...

The Lagrangian point is where the gravitational forces are equal.
The Evolution of Binary-Star Systems

There are different types of binary-star systems, depending on how close the stars are... In a detached binary, each star has its own Roche lobe:

(a) Detached binary

Lagrangian point

Roche Lobes
The Evolution of Binary-Star Systems

In a contact binary, much of the mass is shared between the two stars:
The Evolution of Binary-Star Systems

In a semidetached binary, one star can transfer mass to the other:

“Accretion”
The Evolution of Binary-Star Systems

As the stars evolve, their binary system type can evolve as well.

This is the Algol system: It is thought to have begun as a detached binary.
The Evolution of Binary-Star Systems

As the blue-giant star entered its red-giant phase, it expanded to the point where mass transfer occurred (b).

Eventually enough mass accreted onto the smaller star that it became a blue giant, leaving the other star as a red subgiant (c).
Life after Death for White Dwarfs

A white dwarf that is part of a semidetached binary system can undergo repeated explosions!
Life after Death for White Dwarfs

Material falls onto the white dwarf from its main-sequence companion.

When enough material has accreted, fusion can reignite very suddenly, burning off the new material.

Material keeps being transferred to the white dwarf, and the process repeats, as illustrated here:
Life after Death for White Dwarfs

A Nova is a star that flares up very suddenly and then returns slowly to its former luminosity:

“Nova” = “New Star”
(...well, that’s what they called it...)
Life after Death for White Dwarfs

This series of images shows ejected material expanding away from a star after a Nova explosion:
**TPYXIDIS OUTBURST**

CBET No. 2700 issued on April 15, 2011 reports that the recurrent nova T Pyxidis has been discovered in outburst. It was detected by Mike Linnolt at visual magnitude 13.0 on 2011 April 14, and the outburst has been visually confirmed by several observers.
Mass–Radius Relation for White Dwarfs

notice that radius decreases with increasing mass until the Chandrasekhar limit is reached.

Chandrasekhar limit = 1.4 solar masses
“The End” for a White Dwarf with a close binary companion...

A “Carbon-Detonation” (Type Ia) **Supernova**!
Computer Simulations of a Type Ia SN Explosion “Detonation”!
Vivid View of Tycho's Supernova Remnant
Spitzer Space Telescope / Chandra / Calar Alto

NASA/JPL-Caltech/CXC/Calar Alto O. Krause (Max Planck Institute for Astronomy) sig09-016
Two Alternative Roads to Type Ia White Dwarf Explosion...?
Type Ia Supernovae make great "Standard Candles"!
A high-mass star can continue to fuse elements in its core right up to Iron (after which the fusion reaction is energetically unfavored).

As heavier elements are fused, the reactions go faster and faster!
This graph shows the relative stability of nuclei. On the left, nuclei gain energy through fusion; on the right they gain it through fission:

Iron is the crossing point; when the core has fused to iron, no more (energetically profitable) fusion can take place...
“The End” for a High-Mass \((M > 8 \times M_{\text{Sun}})\) Star...

A “Core-Collapse” (Type II) \textit{Supernova}!
1. Core contracts
2. Core hardens
3. Bounce shock starts
4. Shock stalls
5. Instabilities raise shock
6. Explosion proceeds
As Seen Around the World in 1054 AD...!

Crab Nebula • M1
Hubble Space Telescope • WFPC2

NASA, ESA, and J. Hester (Arizona State University)
The Crab Nebula in Motion

This second set of images, focused in on the central pulsar, shows ripples expanding outward at *half the speed of light*:

- **December 29, 1995**
- **February 1, 1996**
- **April 16, 1996**
Supernovae

This is the Vela supernova remnant: Extrapolation shows it exploded about 9000 BCE:
Supernova 1987A Rings

Hubble Space Telescope
Wide Field Planetary Camera 2
The 2 General Types of Supernova Explosions...

(a) Type I Supernova

Binary star system

White dwarf

Planetary nebula

Detonation

(b) Type II Supernova

Helium, carbon

Hydrogen

Normal star fusion

Heavy elements

Hydrogen

Iron core

Massive star imploding

Core rebound

Remnant core

Shock wave

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Supernovae

A supernova is incredibly luminous—as can be seen from these curves—and more than a million times as bright as a nova:
A Supernova can outshine its *Entire Galaxy!*
The End of a High-Mass Star...

Q: Does anything *survive* the Type II SN *Explosion*?

The inward pressure is enormous, due to the high mass of the star.

There is nothing stopping the star from collapsing further; it does so very rapidly, in a giant implosion.

As it continues to become more and more dense, the protons and electrons react with one another to become **neutrons**:

\[ p + e \rightarrow n + \text{neutrino} \]

The neutrinos escape; the neutrons are compressed together until the whole star has the density of an **atomic nucleus**, about \(10^{15} \text{ kg/m}^3\).
Neutron stars, although they have 1–3 solar masses, are so dense that they are very small. This image shows a 1-solar-mass neutron star, ~10 km in diameter, compared to Manhattan:
The Crab Nebula in Motion

The Crab Nebula is complex; its expansion is detectable and there is a **Pulsar** at its center...