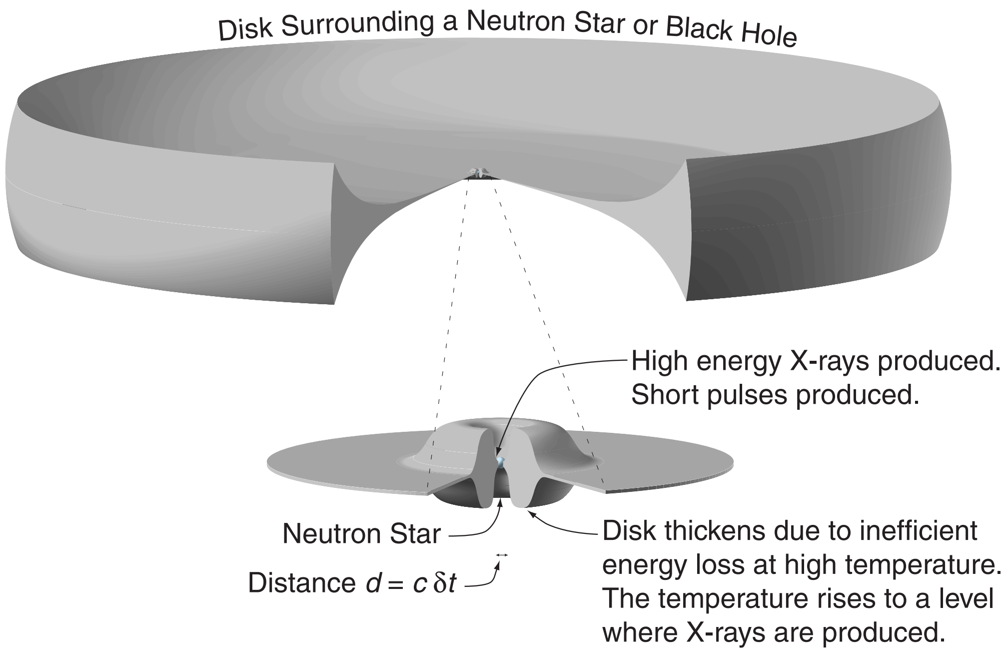
Disks Surrounding Neutron Stars – The X-Ray Binaries

The processes which transfer mass inward and angular momentum outward continue inward toward the gravitational center. In the case of the white dwarf, the stellar surface is encountered at a distance of about 7,000 km or about the size of the Earth. This is about 1% the size of the sun. A neutron star has a size of about 10 km or is about 700 times smaller than the white dwarf. A disk appropriate for a neutron star is shown below:

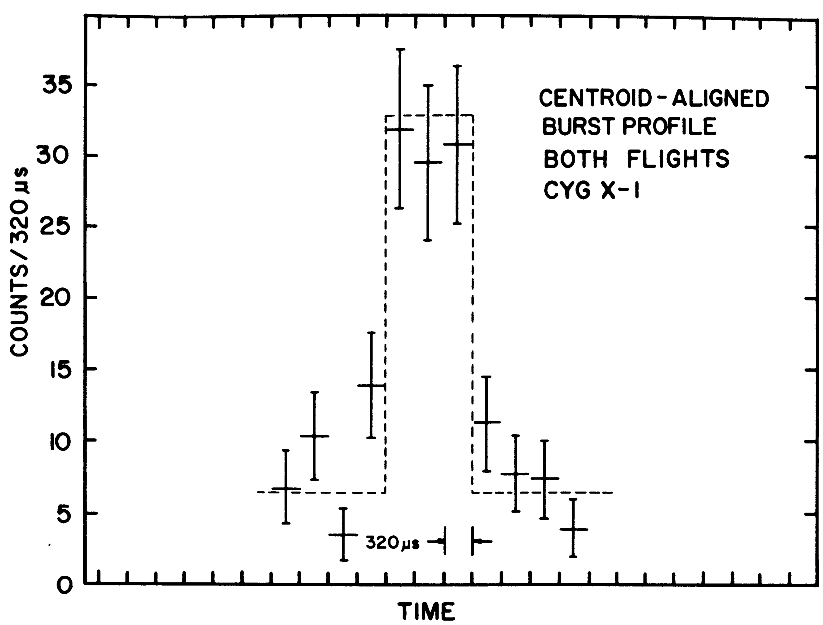


The outer edge is shown at roughly the place where it would have been in the case of the dwarf nova. The processes of frictional heating, mass and angular momentum transport continue through the entire disk. The ability of the disk to radiate away the frictionally generated energy depends on the disk temperature. As the disk becomes more concentrated near the neutron star, the energy dissipation also becomes more concentrated. This requires an ever increasing temperature. At the highest temperatures, the gas becomes mostly ionized (all atoms lose their electrons). The ability of the gas to radiate depends strongly on the presence of electrons attached to the nuclei so that when the gas becomes fully ionized, it becomes more and more difficult to send the energy out into space as radiation. The star overcomes this difficulty by making a transition to very high temperatures. It can then dispose of the energy but due to the high temperature, the type of radiation which comes out is X-rays. In addition, the high temperature causes the disk to swell up. The radiation generated closest to the neutron star cannot escape easily due to the blocking effect of the regions just outside the neutron star.

The Size of the Region Emitting X-Rays

If the ring of matter emitting radiation brightens and fades abruptly due to an abrupt dumping of matter into the inner part of the disk, the light from different parts of the ring will have to travel different distances to reach us. If we are viewing the ring from the side and it has a diameter d, the radiation from the far side will take $\delta t = d/c$ longer to reach us than does the radiation from the near side. The burst of radiation can then be no briefer than δt. Thus if we can measure a burst interval of time δt we can limit d to being no larger than $c\delta t$.

For the important case of Cyg X-1, the X-rays have been observed to come in very brief bursts. The figure below gives a composite burst profile formed by superposing a set of 12 bursts seen over an interval of two years.



This figure shows that the duration of the average X-ray burst from Cyg X-1 is of order 0.001 s or one milli-second. This gives a size of less than 300 km. While this is larger than the neutron star, it is also much smaller than is possible for a white dwarf. Therefore, we conclude that the object in Cyg X-1 must be either a neutron star or a black hole.

Estimation of the mass for the compact star in Cyg X-1

The previous arguement shows that the size of the compact object in Cyg X-1 is smaller than a white dwarf. It is therefore either a neutron star or a black hole. Generally it is agreed that neutron stars cannot have more mass than about 3 times the mass of the sun. Thus the question of the nature of the star in Cyg X-1 becomes a question of determining a lower limit to its mass.

There are four critical measurements and one estimation that lead to a lower limit to the mass of the compact object:

1. The orbital period is 5.6 days. This is solid.

2. There are no eclipses of the X-ray source. This is solid and implies that the angle between us and the plane of the orbit is larger than some limit which depends on the size of the optical star.

3. The apparent brightness of the optical star can be measured. This is solid but needs to be corrected for the dimming effect of interstellar matter.

4. The surface temperature can be determined from the star color. This is a bit less certain but still pretty good. The color also has to be corrected for the effect of interstellar matter.

The period combined with the non-eclipse constraint yield a combination of factors which includes the mass of the compact object and the radius of the optical star. The luminosity and surface temperature can yield an estimate of the radius of the optical star if the distance is known. Thus the final key ingredient is an estimate of the distance to the optical star. From a variety of indirect arguements, it is thought that the distance is larger than 2500 parsecs or 8200 light years. These results all combine to yield:

$$M_{\text{Compact}} > 5.3 M_{\odot}$$

General Properties of X-ray Stars

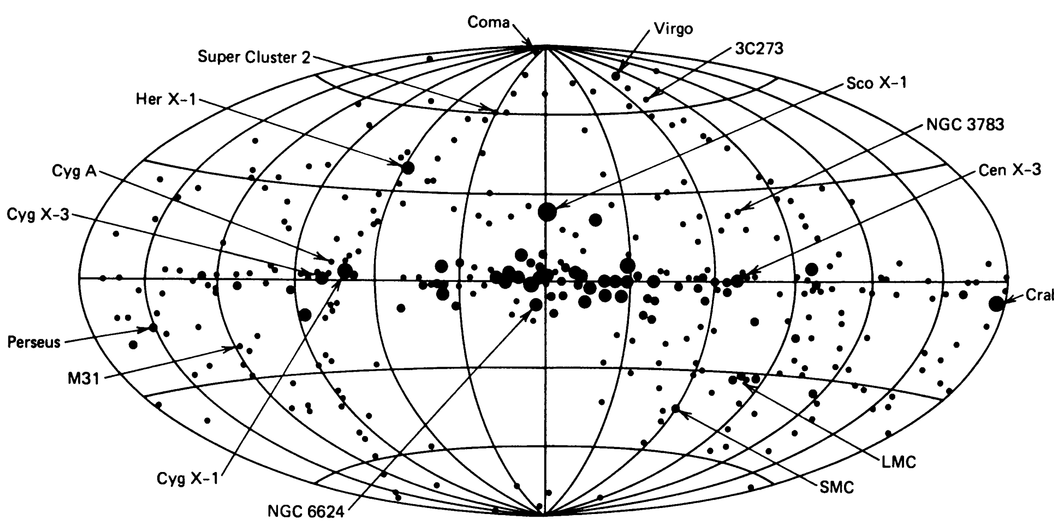
The X-ray binaries are generally classified as:

- High Mass X-ray Binaries
- Low Mass X-ray Binaries

The break point is at $1M_\odot$ for the mass losing star.

- The low mass cases may be the product of the Type Ia supernova where a neutron star is formed and the system is not disrupted.
- The high mass cases may be related to a group of objects called Wolf-Rayet Stars which are binaries that are ejecting matter at a rapid rate. They may be in the common envelope phase of evolution. The high mass cases include the black hole candidate systems like Cyg X-1

One way of characterizing the X-ray objects is by their distribution in the galaxy:



The size of the dot is proportional to the apparent X-ray brightness.

Types of Supernovae

The supernovae are broadly classified by the elements they show in their spectra. The first level classification comes from Hydrogen:

- Supernovae which show no Hydrogen are Type I
- Supernovae which show Hydrogen are Type II

There is a further subclassification of the Type I supernovae into types Ia, Ib and Ic. The distinction comes from the shape of the light curve and the presence of some emission lines of Oxygen and Calcium at late stages of the evolution.

Type Ia These are thought to be the mass accreting white dwarfs which are pushed over the edge to collapse into neutron stars. This type appears in all types of galaxy.

Type Ib These have high Helium abundance. They only occur in the spiral arms of galaxies and not in elliptical galaxies.

Type Ic These are mostly Carbon and are distributed like the Type Ib's.

Based on these considerations, it is believed that the Type II as well as the Types Ib and Ic are the products of higher mass stars whereas the Type Ia is from low mass progenitors.

Binary Star Mass Transfer Cases

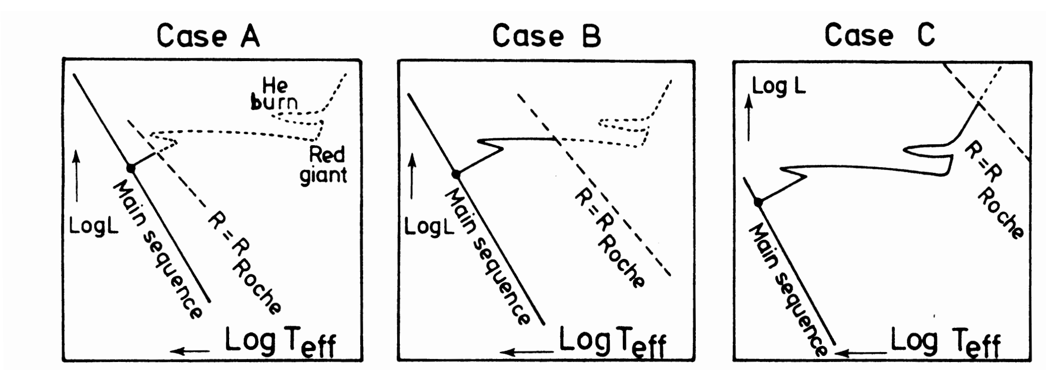
Due to the wide range of variable which can influence the evolution of a binary system and the range of outcomes in terms of supernova explosions, we have to step back and look at the things which are possible from the point of view of the prior stellar evolution. There is a broad classification system which gives three Cases of binary evolution:

Case A Mass transfer begins on the main sequence.

Case B Mass transfer begins prior to Helium ignition.

Case C Mass transfer begins after the formation of the Carbon or Helium core supported by quantum pressure.

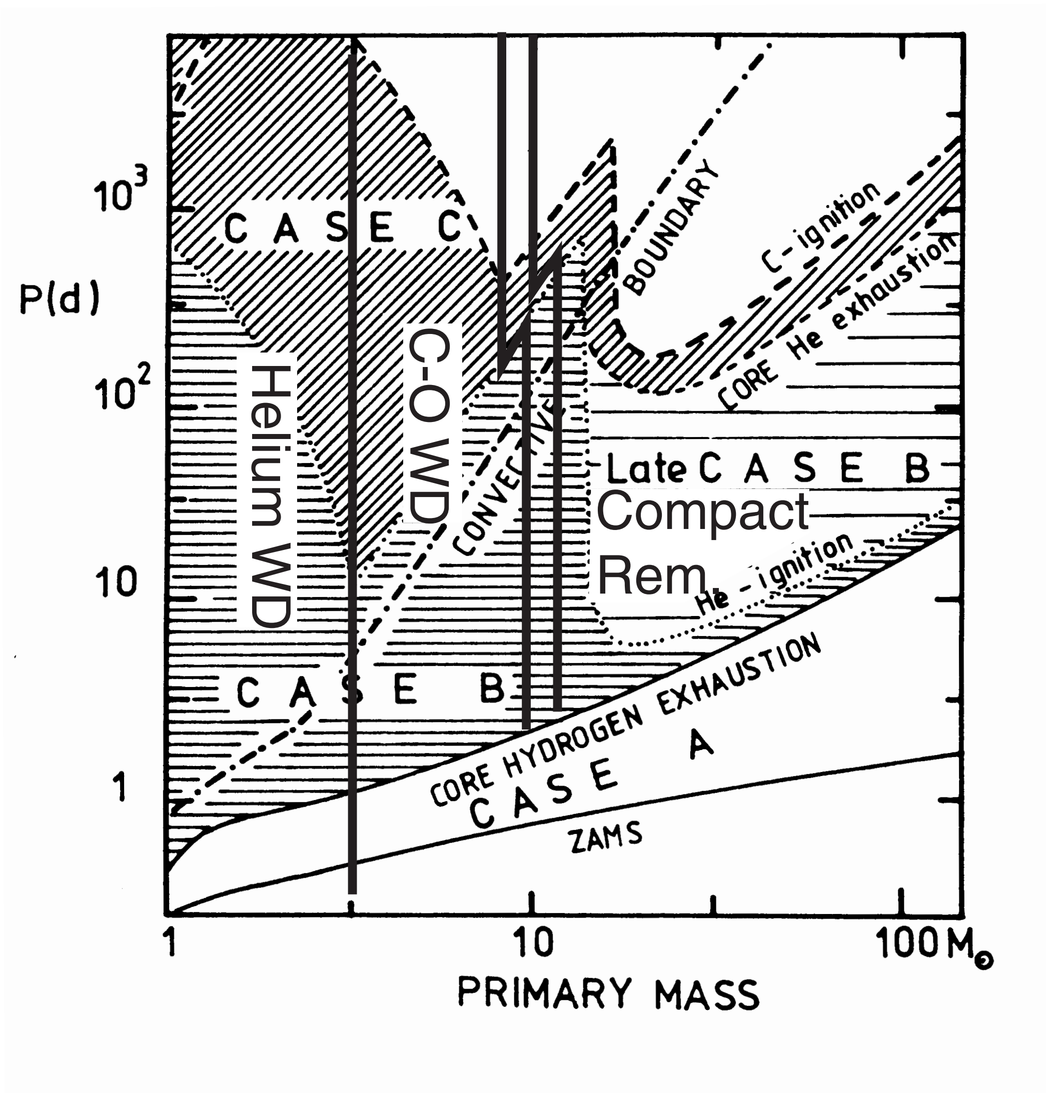
The positions on the HR Diagram are shown below:



The Case A is quite rare and most cases are B and C. It is usual for the transfer, especially in Case C, to occur rapidly. Mass and angular momentum are probably lost to the pair during the transfer. In the Case C, the core of the mass losing star is sufficiently compact that it cannot be lost to the system and is largely unaltered by the transfer.

Binary Star Evolution Scenarios

The subsequent evolution of the part of what was initially the more massive star depends on the mass it had and its composition. The initial separation depends on the mass of the primary and the orbital period. The overall possibilities are summarized in the diagram below:



The Type I Supernovae probably come from the section labeled C-O WD since those white dwarfs can ignite their Carbon and Oxygen following additional transfer. These leave no remnant and are completely disrupted. Neutron stars can be formed from the more massive cases which will undergo an Iron evaporation collapse with the bounce to yield a supernova which does not disrupt the whole star.