Lec 29: 12/09/2010

Binary Stars and Accretion:

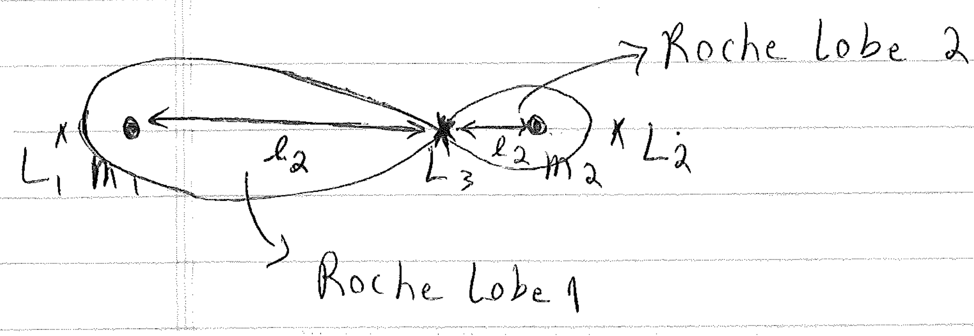
The discussion of stellar evolution throughout this course concentrated on the star as a single dynamical entity that is not influenced by its surroundings. The evolutionary phenomena change significantly and new effects come into play if the star is a member of a binary system. The chances that a given star is gravitationally bound to another star is fairly high and well over half of all the stars in the sky are members of binary or multiple star systems.

When the stars are reasonably far away, compared with the sum of their radii, the influence of one star on another is minimum. The situation becomes more complicated if the separation between the stars is not far enough, and the radius of one of the stars becomes significantly large.

We can quantify this aspect by studying the "Reduced Three-Body Problem". This is a system consisting of three masses m_1, m_2, m_3 such that:

- $m_3 << m_1, m_2$.
- m_3 does not affect the motion of m_1 and m_2.
- m_3 moves in the orbital plane of m_1 and m_2.

The orbit of $m_1 - m_2$ is elliptical (for gravitationally bound masses). There are 5 Lagrange points L_1, L_2, L_3, L_4, L_5 at which m_3 corotates with m_1 and m_2. Three of these L_1, L_2, L_3 are on the same line that connects m_1 and m_2. These three points and one equipotential curve of the $m_1 - m_2$ system are shown below:



The distances ℓ_1, ℓ_2 of the two masses from L_3 are given by:

(a: semi-major axis of $m_1 - m_2$ orbit)

$$\ell_1 = a\left[1.00 - 0.114 \log\left(\frac{m_2}{m_1}\right)\right] \quad , \quad \ell_2 = a\left[1.00 + 0.114 \log\left(\frac{m_2}{m_1}\right)\right]$$

Note that $\ell_1 > \ell_2$ if $m_1 > m_2$.

The important point is that L_1, L_2, L_3 are unstable equilibrium point. This implies that if the radius of m_1 becomes large enough to fill Roche lobe 1, then the material that reaches L_3 can flow to m_2. It is convenient to define a length scale R_{RL} as the radius of a sphere that has the same volume as the region bounded by the Roche lobe. To a good approximation:

$$\boxed{R_{RL,1} \simeq a\left[\frac{0.49\, q^{\frac{2}{3}}}{0.6\, q^{2/3} + \ln(1+q^{\frac{1}{3}})}\right] \quad , \quad q \equiv \frac{m_1}{m_2}}$$

As one of the stars in the binary system evolves, its radius changes during various phases. For example, in a $\simeq 5 M_\odot$ star the radius increases by a factor of $\lesssim 2$ during the core Hydrogen burning, by a factor of ~ 10 during the shell Hydrogen burning, and by another factor of ~ 10 during the phase preceding the core Carbon burning.

As long as $R_1 < R_{RL,1}$, the evolution of m_1 can be approximated as that of an isolated system. However, when $R_1 \gtrsim R_{RL,1}$, the stellar material fills the Roche lobe and significant mass transfer can take place from m_1 to m_2. The mass transfer decreases $R_{RL,1}$, as well as R_1. If the net effect is to decrease R_1 below $R_{RL,1}$, then the mass transfer will cease. In the opposite case, mass transfer will continue at a significant rate.

The behaviour of the system depends essentially on how the Roche lobe radius and the stellar radius vary in response to changes in m_1.

It is straightforward to find:

$$n_L \equiv \frac{\partial \ln R_{RL,1}}{\partial m_1} = -2(1-q) + \frac{2}{3}(1+q)\left[1 - \frac{0.6\,q^{\frac{2}{3}} + 0.49\,q^{\frac{1}{3}}(1+q^{\frac{1}{3}})^{-1}}{0.6\,q^{\frac{2}{3}} + \ln(1+q^{\frac{1}{3}})}\right]$$

This slope is a monotonically increasing function of q and has the limiting value of $-\frac{5}{3}$ for $q \to 0$. It represents how fast the Roche lobe radius shrinks as m_1 decreases.

To decide about the stability of mass transfer, we also need to determine how the radius of the star varies with m_1, which is represented by the following index:

$$n_* \equiv \frac{\partial R_1}{\partial m_1}$$

This index depends on the quantity that is kept constant during the mass transfer. If the star has a fixed chemical composition and remains in thermal equilibrium, then for main sequence stars over a mass range of $(0.1-10)\,M_\odot$ we have $\underline{\underline{n_* \simeq 0.7}}$. On the other hand, if the mass transfer maintains hydrostatic equilibrium (but not necessarily thermal equilibrium) we have $\underline{\underline{n_* \simeq -\frac{1}{3}}}$ for stars with mass $\lesssim 0.7\, M_\odot$ (which are fully convective) and $\underline{\underline{n_* \simeq 2}}$ for stars with mass $\gtrsim 10\, M_\odot$ (which have radiative envelopes).

One consequence of mass transfer will be the changes in the orbital characteristics of the binary system, which are essentially determined by the masses of the stars. In fact, the system becomes fairly distorted when any one of the stars fills its Roche lobe and the orbital characteristics changes quite a bit.

More importantly, the evolution of the individual stars can be significantly modified by mass transfer. As we have seen, the mass of the star is the single governing parameter that determines its entire evolution. This, however, assumed that the mass remains constant (except possibly for mass loss by stellar winds). If a significant amount of mass transfer occurs, then the evolutionary history of a star can be very different. For example, consider the situation in which $m_1 > m_2$ initially. Being more massive, m_1 evolves faster, enters the red giant phase, and fills its Roche lobe. A significant amount of mass transfer can make $m_2 > m_1$. As a result, m_2 will now evolve faster, and could end up in a supernova explosion, and leave behind a compact object. Observation might then indicate an apparently paradoxical situation where the star with larger mass seems to be less evolved.

It is possible to have binary systems with one member (or both) to be a compact stellar remnant. Such systems show a variety of interesting behaviour. Broadly speaking, the following possibilities can be distinguished:

(1) White dwarf + a normal star as companion. The gravitational force of the white dwarf pulls out the matter from the companion and, under certain conditions, could form an accretion disk around it. The accreted material (Hydrogen or Helium) burns on the surface of the white dwarf in a runaway process and produces a flash, called a nova.

(2) Neutron star + a low mass star as companion. Because of the much stronger gravitational field of neutron stars (compared with white dwarfs) burning of the accreted material gives rise to higher temperatures, leading to radiation that peaks in the X-ray band. The low mass X-ray binaries (LMXB) belong to this class.

(3) Neutron star + a high mass star as companion. This case is

similar to (2), and called a high mass X-ray binary (HMXB).

(4) Pulsar a compact remnant as companion. The radiation from the pulsar allows precise measurement of orbital parameters of the system, and theoretical models can be tested accurately. General relativistic effects become important when both the stars are pulsars or neutron stars. Then it is possible to use the binary system to test the strong field predictions of general relativity. For example, the decrease in the orbital period of the binary pulsar (discovery by Hulse & Taylor in 1974, Nobel prize in 1993) indicates radiation of gravitational waves by this binary system.