PHY20003 ASTROPHYSICS

Lecture 21 Evolution of close binaries

21.1 Close binaries

As briefly mentioned in Lecture 18, only about 30% of the stars near the Sun are single, the rest are in binary (or higher multiple) systems.

About the half of these, in turn, will at some point in their lives consist of close or interacting binaries where the two components cannot complete their normal evolution due to the presence of the companion. This is because the surface of the star is distorted by the gravitational force of the companion, which in turns affects the stellar structure and evolution.

In addition, the process of accretion of material from a companion can also dramatically alter the evolutionary path of a star.

Close or interacting binaries can produce some of the most exotic inhabitants of our Universe, including X-ray binaries containing black holes, white dwarf – white dwarf binaries, and double neutron star systems.

21.2 Synchronism and Circularisation of orbits

The gravitational influence of a nearby massive companion can raise tides on the stellar surface. These tides, in turn, will create a torque that can transfer energy and angular momentum from the star to the orbit.

In other words, the tides cause the dissipation of energy. As the star rotates, the tidal bulge that runs across the star causes friction. This lost energy is extracted from the star's rotational energy and its orbital energy.

Eventually, tides will force the stars to rotate on their axes in the same period as their orbital period. This stops further dissipation from the fluid friction generated by the tides traversing the stellar surfaces. At this point, the stars are in *synchronous rotation* and will also cause the stellar orbits to become circularised over time.

There are two parts to the tide which causes energy dissipation:

- <u>Equilibrium tide</u>: – the hydrostatic adjustment of the structure of the star to the perturbing force exerted by the companion
- <u>Dynamical tide</u>: – the dissipation of energy in a fluid by means of viscous effects in the turbulence, convection or by radiative damping. Some energy will go into the free modes of oscillation of a star. Dynamical tides typically have a much smaller effect than equilibrium tides.

<u>Time scales</u>

The timescales for synchronisation (t_{sync}) and orbital circularisation will depend both on the mass ratio, M_1/M_2, and the orbital period, P_{orb}. Characteristic timescales for a system with $M_1/M_2 = 1$ are given in Table 21.1

Table 21.1: Time scales for rotational synchronisation and orbital circularisation for an equal mass binary $(M_1/M_2 = 1)$

P_{orb}	t_{sync}	t_{circ}
10 d	10^8 yr	10^{11} yr
1 d	10^4 yr	10^6 yr

21.3 The Roche Lobe

The shape of the distorted star(s) in close binaries can be obtained via the Roche approximation, which assumes that the gravitational field of the star is the same as if there is no distortion (equivalent to concentrating all the mass of the star at its centre).

Assuming that the component stars are tidally locked, and that the orbits are circularised, the Roche approximation gives the sum of the gravitational potentials of the two components, plus an effective potential from the fictitious centrifugal force due to the stars' rapid rotation. We can use this approximation to plot gravitational equipotential contours in the plane of the orbit.

Figure 21.1: Rough sketch of the figure-of-eight critical potential given by the Roche approximation

The figure-of-eight contour is known as the critical potential, and the two cusped volumes are known as the Roche lobes.

There are five Lagrangian points, $L_1,\ L_2,\ L_3,\ L_4,\ L_5$, where the effective gravitational force is zero. The inner-Lagrangian point, L_1, lies between the two stars, and defines the point at which material is attracted to one star or the other.

From the gravitational equipotential contour plot, we can clearly distinguish 3 generic type of binaries.

21.3.1 Detached systems

When both components of a binary are sufficiently small (relative to its Roche lobe) and/or their separations are relatively large, each star will lie well within its Roche lobe, and will be relatively undistorted.

21.3.2 Semi-detached systems

As the component stars evolve, they will expand and gradually fill their potential wells. The more massive star will expand until it reaches the L_1 point and its surface lies on the Roche lobe. Further expansion causes material to flow into the companion's potential well (through the L_1 point), and mass transfer and accretion begins.

21.3.3 Contact binaries

Finally, if both stars till their Roche lobes, the two stars will actually touch, forming a contact binary! They may overfill their Roche lobes until matter is lost through the L_2 point.

21.4 The Algol Paradox

Algol is the 2nd brightest star in Perseus (β Persei), and is famed for being the prototype of the class of eclipsing binaries.

The system is a semi-detached binary, with a K-type subgiant star transferring material to a B-type companion.

Example: The K-type subgiant star in the Algol system has a mass of 0.8 $M_\odot$, whereas the B-type companion has a mass of 3.7 $M_\odot$. If the lifetime of the Sun is 10^{10} years, estimate their lifetime.

We would expect the subgiant, which is the more evolved star in the system, to be the more massive one (remember from Lecture 18 that more massive stars have a shorter main sequence lifetime). However, it is actually the less massive component in the system! This cannot be explained in terms of single star evolution,

To explain this, we need to include its binary companion into the picture. Originally, the subgiant was the more massive star, but as it evolved, it started to first film and subsequently overflow its Roche lobe and transfer mass onto its companion until it became the less massive component of the binary!

21.5 New Evolutionary paths

Mass transfer in close binaries can dramatically alter the evolutionary path that the component stars follow. The fate of such systems is largely governed by their initial masses.

Close binaries with lower mass components may evolve to become Algol systems, cataclysmic variables, or white-dwarf binary pairs. These systems can also lead to Type Ia supernovae (important for measuring the distance scale of the Universe).

On the other hand, close binaries with high mass component may be the progenitors of X-ray binaries, binary pulsars (an important test-bed for general relativity, and a source of gravitational waves), bow-shock pulsars, and even binary black-hole systems.