Lecture 12: Accretion

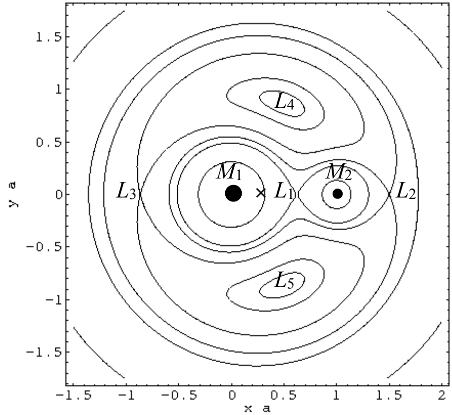
Senior Astrophysics

2018-04-17

Outline

Roche lobes

Last lecture, we introduced a description of gravity in a rotating coordinate system.



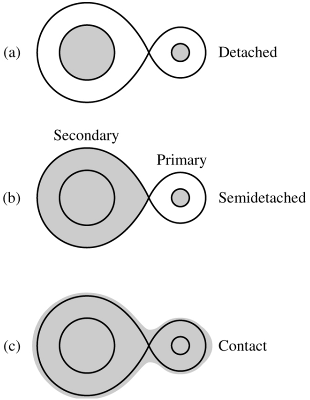
Classes of binary star systems

- The inner Lagrange point, L_1, is the most important for interacting binary stars.
- One contour of the Roche potential intersects itself at the L_1 point. This figure-8 contour is called the Roche potential.
- The teardrop shaped regions defined by this contour are called Roche lobes, and define the gravitational domain for each star.

Classes of binary star systems

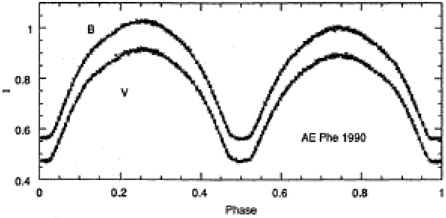
- The appearance of a binary star system depends on which equipotential surfaces are filled by the stars.

- detached: both stars are within their Roche lobes and relatively undistorted
- semi-detached: one star has expanded to fill its Roche lobe and is highly distorted
- contact: both stars fill their Roche lobes and touch at the L_1 point.

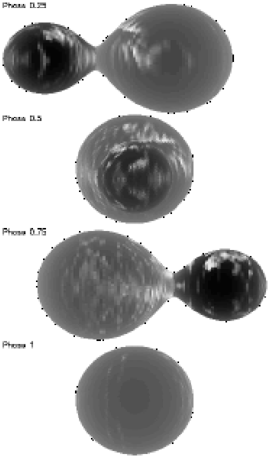


Carroll & Ostlie Fig. 18.4

Classes of binary star systems



Contact binary AE Phoenicis: light curve and model, from Maceroni et al. A&A 288, 529 (1994)



Contact binary AE Phoenicis: light curve and model, from Maceroni et al. A&A 288, 529 (1994)

Classes of binary star systems

- If a star expands to touch the Roche surface, we can get mass transfer: material can flow through the inner Lagrange point and onto the companion.
- Things become interesting when one star's surface gets close to the Roche potential. That's when a regular binary turns into an interacting binary.

Accretion

- Accretion is vital in many areas of astrophysics:
  - Stars, planets and galaxies grow by accretion
  - Quasars are powered by accretion
  - Novae and type Ia supernovae are triggered by accretion
- Accretion liberates gravitational potential energy, making accreting objects potentially very powerful sources of energy.

Accretion energy

- Let's make a quick estimate of how much energy can be released through accretion. Consider a mass $m = 1$ kg which starts at rest far from a star with mass M and radius R. The initial total mechanical energy of the mass is
$$E = K + U = 0$$
- As it approaches the star's surface, potential energy is converted into kinetic energy, so using conservation of energy
$$K = -U = G\frac{Mm}{R}$$
- On impact with the star, this kinetic energy is converted into heat and light.

Accretion energy

- Thus the gravitational energy release per unit mass is

$$\Delta E_{\text{acc}} = \frac{GM}{R}$$

which increases with **compactness** M/R: for a given M, the yield is greatest for the smallest accretor radius R.

Accretion energy

- Consider the amount of energy released by 1 kg of infalling matter onto different objects:
  - *White dwarf*: $M = 0.85 M_\odot$, $R = 6.6 \times 10^6\,\mathrm{m} = 0.0095\, R_\odot$

$$\Rightarrow \Delta E_{\mathrm{wd}} = \frac{GM}{R} = 1.71 \times 10^{13}\ \mathrm{J}$$

    which is 0.019% of the rest energy (mc^2); $\varepsilon \sim 0.0002$
  - *Neutron star*: $M = 1.4 M_\odot$, $R = 10\,\mathrm{km}$

$$\Rightarrow \Delta E_{\mathrm{ns}} = 1.86 \times 10^{16}\ \mathrm{J} \Rightarrow \varepsilon \sim 0.21$$

Recall that the energy released by the fusion of 1 kg of H is

$$0.007 mc^2 = 6.29 \times 10^{14}\ \mathrm{J} \Rightarrow \varepsilon \sim 0.007$$

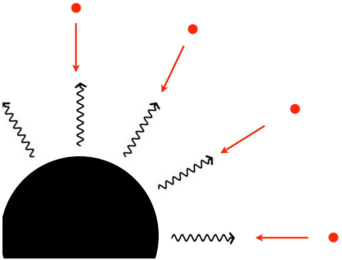
Hence **accretion is the most efficient known way of getting energy from matter**; accreting neutron stars are sources of immense amounts of energy.

The Eddington limit

- The luminosity of an accreting system is proportional to the mass accretion rate. However, a higher luminosity leads to a higher radiation pressure on the infalling matter. Eventually, the outward radiation pressure exceeds the inward gravitational pull, and further accretion is prevented. This is called the Eddington limit.

The Eddington limit

- Each photon has energy $h\nu$, momentum $h\nu/c$. So if the source has luminosity L, then the number of photons is $L/h\nu$, and the number of photons per unit area is
$$f = \frac{L}{h\nu.4\pi R^2}$$
at a distance R from the source, assuming spherical symmetry.



- Consider forces on infalling material, assuming matter is hydrogen

The Eddington limit

- **Inward force** is gravitational force

$$F_{\text{grav}} = \frac{GM(m_p + m_e)}{R^2} \sim \frac{GMm_p}{R^2}$$

- **Outward force** is radiation pressure, which acts on electrons in the infalling material via the Thompson cross-section σ_{T}. Each electron intercepts $\sigma_{\text{T}} f$ photons, so force on each e^{-}–p pair is

$$F_{\text{rad}} = \frac{h\nu}{c} \times \sigma_{\text{T}} f = \frac{h\nu}{c} \times \frac{\sigma_{\text{T}} L}{h\nu . 4\pi R^2} = \frac{\sigma_{\text{T}} L}{4\pi c R^2}$$

The Eddington limit

- The forces balance when $F_{\rm rad} = F_{\rm grav}$:

$$\frac{\sigma_{\rm T} L}{4\pi c R^2} = \frac{G M m_p}{R^2}$$

This gives a constraint for the maximum accretion luminosity, when the outward pressure of radiation equals the inward gravitational force:

$$L_{\rm Edd} = \frac{4\pi c G m_p M}{\sigma_{\rm T}}$$

the Eddington limit.

The Eddington limit

- The Eddington limit depends only on the **mass** of the accretor:

$$L_{\rm Edd} = 1.26 \times 10^{31} \left(\frac{M}{M_\odot} \right) \text{ W}$$

- Higher mass objects have higher Eddington limits, so we can use the Eddington limit to put a lower limit on the mass of an accreting object.
- Note that our derivation assumed spherical symmetry, and that the accreting mass is hydrogen.

Website of the Week

arXiv.org
Preprint server, mainly Physics, but also Mathematics, Computer Science, Quantitative Biology, Quantitative Finance and Statistics

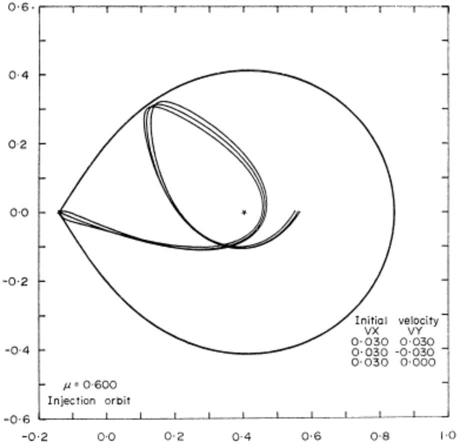
Modes of accretion

There are several ways that accretion can occur in binary systems:

- If one star is filling its Roche lobe, then matter can stream through the L_1 point and be captured by the companion: Roche-lobe overflow
- Even if the stars are not close enough for Roche-lobe overflow to occur, mass from a strong stellar wind can be captured by the other star: wind-driven accretion

Accretion disks

- Because the gas has large angular momentum, it cannot fall directly onto the surface of the accreting star.



from Flannery 1975, MNRAS 170, 325

- Instead, it falls through the L_1 point and goes into orbit around the second star. On the return it intersects itself, and friction makes it spread, first into a ring, and then a disk: an accretion disk.

Accretion disks

- Because $v_{\|} \sim c_s \ll v_{\rm ff}$, where $v_{\rm ff}$ is the velocity acquired by the particle as it is falls towards the primary, initial conditions at the L_1 point have little influence on the accretion trajectory.
- The collisions of particles on intercepting orbits will heat the disk, which can then emit energy as EM radiation.
- To conserve energy, some particles must spiral inwards; but this requires angular momentum to be lost, so other particles must spiral outwards.
- Thus we may view an accretion disk as a way to slowly lower particles in the gravitational field of the primary, until they accrete on the surface of the primary.

Observations: X-ray

- As material works its way to the centre of the disk, it heats up. Temperatures reach in excess of 10^5 K for white dwarfs and 10^7 K for neutron stars.
- $\Rightarrow$ compact binaries are powerful sources of high-energy (X-ray and UV) radiation.

Observations: Optical

- Optical telescopes can see light from the accretion disk, as well as light from the (distorted) companion star.
- Lines from the accretion disk have a characteristic double-peaked shape

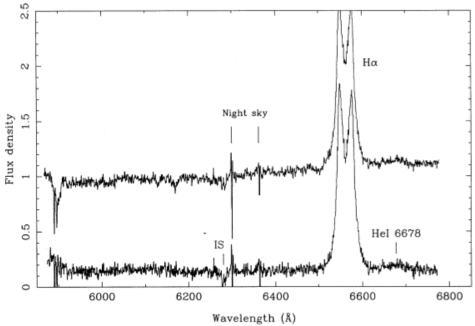
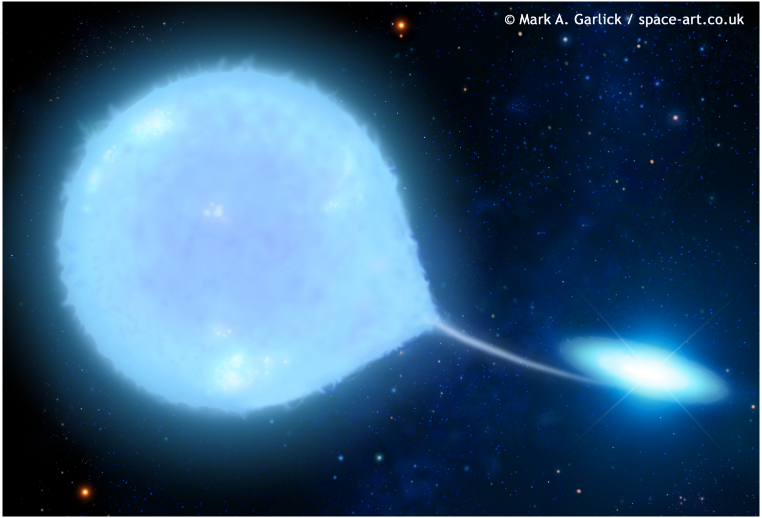


Figure 4. The average spectrum of A0620 − 00 in our rest frame is plotted along with the same spectrum after subtraction of the K star from each spectrum before averaging. The result is the spectrum of the disc and bright-spot. Apart from the strong Hα line, weak He I 6678 and possibly He I 5876 emission is visible. For reference, before sky subtraction, the brightest night-sky line at 6300 Å was 100 times brighter than A0620 − 00 over the spatial extent of the stellar image.

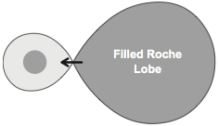
from Marsh et al. (1994)

Not observations

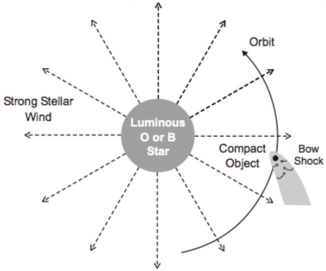


Wind-driven accretion

- Wind-driven accretion is understood much less well than accretion by Roche-lobe overflow
- Particularly important for binaries containing massive stars (O and B stars)
- Only a tiny fraction (0.01–0.1%) of the matter in the wind is accreted onto the companion, unlike RL overflow (close to 100%)



Roche Lobe Overflow
(Low-Mass X-Ray Binaries)



Wind-Driven Accretion

Wind-driven accretion

- We will not necessarily get an accretion disk in wind-driven systems; the angular momentum of the transferred particles makes it less probable than in Roche-lobe overflow.
- However, some wind-driven systems do show evidence of accretion disks.

Next lecture

Binary evolution

- Conservative and non-conservative mass transfer
- Cataclsymic variables
- Type Ia supernovae