Questions and Answers for Stellar Physics

Q1: What is a star?

A1: A luminous sphere of gas, characterised by an equilibrium between gravity and pressure.

Q2: What is the problem with the definition of the stellar radius via $\tau_\lambda(R_\star) = 2/3$?

A2: This definition depends on the wavelength λ and is therefore not unique. To make it unique, one has to either introduce a mean opacity (a suitable average of the opacity over wavelengths) or one has to pick a "representative" wavelength. In fact, different stellar atmosphere codes use different definitions here.

Q3: Is $T_{\text{eff}} = T(R_\star)$?

A3: Mathematically speaking, the answer is no. The physical temperature at the position of the stellar radius $R_\star$, as defined above, must not necessarily coincide with T_{eff}. T_{eff} is introduced via the total radiative flux, not by any physical temperature in the stellar atmosphere.

Q4: Why is m_λ-M_λ called the distance modulus?

A4: If m_λ has been measured and the spectral type of the star can by determined from its spectrum, one can look up its absolute magnitude in catalogues. Therefore, one can compute a "spectroscopic" distance d from m_λ-M_λ. This is an important technique, an easy (though not very precise) way to determine the distance of a star.

Q5: What did Fraunhofer actually prove?

A5: He proved that the sun is made of the same elements as the Earth. The physical laws valid on Earth can be applied to the radiation physics in the sun. This was disputed in his time.

Q6: Why are there no stable stars with $M_\star > 95 M_\odot$?

A6: More massive stars are much larger (much larger $R_\star$) and have higher $T_{\rm eff}$, i.e. higher total radiative fluxes going through their atmospheres. In the ionised atmosphere, the dominating opacity is Thomson scattering on free electrons. As the gas absorbs the radiative flux it also absorbs the outward directed momentum of the photons which leads to an additional outward force – radiation pressure. For too massive stars, radiation pressure would exceed gravity, know as the "Eddington limit", which prevents such stars from forming. However, these limits are disputed (see e.g. https://en.wikipedia.org/wiki/R136a1), and the lifetimes of such stars become so short that star formation, mass loss by winds and stellar evolution all merge into a single time-dependent phenomenon, without ever establishing a static equilibrium characterising the main sequence.

Q7: How is a "star" called which has $M_\star < 0.08 M_\odot$?

A7: It's called a brown dwarf. Brown dwarfs do not reach high enough temperatures to burn hydrogen in their cores, instead they gain most of the energy that they radiate away by slow contraction, which liberates gravitational potential energy. However, they do burn deuterium in early phases.

Q8: Why does the main sequence form a line in the H-R diagram?

A8: A star of mass $M_\star$ will relax relatively quickly toward a particular equilibrium structure as long as it can burn hydrogen in its core. This equilibrium structure on the main sequence is characterised by a certain effective temperature $T_{\rm eff}$ and a certain luminosity $L_\star$, hence with a certain position in the H-R diagram. Therefore, main sequence stars form a one-dimensional sequence of equilibrium states which can be ordered by $M_\star$. In a two-dimensional diagram, this one-dimensional manifold forms a line.

Q9: What are white dwarfs (and neutron stars) made of?

A9: Consider the following mental experiment. Take a gas of mass M and confine it by some force into a certain volume V. In a main sequence star, that force is given by the self-gravity, and the volume will adjust itself to a certain equilibrium value where gas pressure balances gravity. The existence of a stable equilibrium solution is guaranteed because gravity scales as $1/r^2$ whereas the pressure scales as $1/r^3$.

Next, consider an increase of the force.

As we compress the highly ionised gas further, there comes a point where the electrons in the gas are squeezed together so closely that they start to behave like in condensed matter. The Pauli exclusion principle disallows them to occupy the same quantum state, and therefore, each electron must occupy a different energy level. Once all low-lying energy states are occupied, additional electrons need to occupy ever higher energy levels. This energy requirement to compress the material manifests as a pressure. The resulting state of matter is called "degenerate", similar as in a liquid or a solid state, but at extreme temperatures and pressures. Gravity is now balanced by the repelling electro-magnetic forces between degenerate electrons. This is what happens in the burnt-out cores of red giants. As soon as the nuclear fuel is exhausted, such that compression doesn't trigger any new nuclear reactions, the gas collapses to form a degenerate core mostly consisting of carbon, oxygen and nitrogen. Later, after the star has expelled its gaseous envelope in form of massive stellar winds and a planetary nebula, these cores are found as **white dwarfs**. A typical white dwarf is half as massive as the Sun, yet only slightly bigger than Earth, with a mean density of $\sim 10^9\,\mathrm{kg/m^3}$. This form of matter cannot be compressed any further, or can it?

Next, consider an increase of the force.

As we compress the matter further, there comes a point where gravity wins over the electron-magnetic force, and the electrons are squeezed into their nuclei. A "soup of neutrons" forms, where – like in a gigantic atomic nucleus – neutrons "touch" each other, the neutrons are kept at a distance from each other by the strong nuclear force, and this force can again resist gravity. To our knowledge, this extreme form of matter can only be produced during a supernova explosion and the created **neutron stars** (pulsars) are indeed often found at the centres of type II supernova explosions. Neutron stars are made of the densest form of matter known to exist, with a radius of only about 10 km and a mass of about $2\,M_\odot$, which translates into a mean density of $\sim 3 \times 10^{17}\,\mathrm{kg/m^3}$. This form of matter cannot be compressed any further, or can it?

Next, consider an increase of the force.

Once gravity overcomes the barriers of the strong force, there is no stopping. There is *no force known to mankind* which would be able to stop gravity, which increases further as $\propto 1/r^2$. The contraction will continue to form a mathematical discontinuity – a **black hole**.