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Exercise 5

Problem 1: Ionization by a luminous blue variable star

Luminous blue variable (LBV) stars are the brightest stars in galaxies. They are evolved, massive ($M > 50 M_\odot$) stars which may undergo episodes of very strong mass loss, where they lose within a time scale of a year about one solar mass due to an instability in the atmosphere. After such an event the lost material forms a dense, dusty envelope around the star, so that the UV-visual radiation is efficiently absorbed and re-radiated by the dust in the far-IR. Because the envelope expands, the star becomes again visible, a few years or decades after such an event. The most famous example of such a star is η Car.
In this exercise we make estimates about the photo-ionization equilibrium for the gas surrounding such a star assuming that the nebula is homogeneous (constant density), spherically symmetric and consists only of hydrogen. Two types of nebula are considered: a dense nebula (i.e. from a previous mass loss episode) with a density of $N_e = 10^5\,\mathrm{cm}^{-3}$ **or** a nebula of diffuse gas with $N_e = 10\,\mathrm{cm}^{-3}$ typical for the surrounding interstellar medium. We further assume that the star has a luminosity of ionizing photons of $Q(H) = 10^{50}\,\mathrm{s}^{-1}$ ($\approx 10^6$ $\mathrm{L}_\odot$). The temperature in the ionization region is $T_e = 10^4$ K and the H I recombination coefficient to be used is $\alpha_B(10^4\ \mathrm{K}) = 2.6 \cdot 10^{-13}\ \mathrm{cm}^3\,\mathrm{s}^{-1}$.

a. Strömgrenradius r_s: Calculate r_s [in pc] for the dense nebula $N_e = 10^5\ \mathrm{cm}^{-3}$ and the diffuse gas nebula with $N_e = 10\,\mathrm{cm}^{-3}$.

b. Calculate the total mass in $\mathrm{M}_\odot$ for the ionized gas in the dense nebula and the diffuse gas assuming that both regions are radiation limited.

c. Let's assume that the LBV has a mass loss episode in which a dense shell is ejected and the ionizing radiation is switched off (absorbed by the dust in the shell). How much time (typical time scale) is required for the recombination of the dense nebula ($N_e = 10^5\,\mathrm{cm}^{-3}$) or the diffuse gas ($N_e = 10\,\mathrm{cm}^{-3}$)?

d. The ejected shell has a mass of 1 $\mathrm{M}_\odot$ and a gas velocity law like an explosion (or a Hubble flow) $v(r < r_{\max}) = v_{\max} \cdot r/r_{\max}$, where $v_{\max} = 1000$ km/s and $r_{\max} = v_{\max} t$. This shell is ionized by the star during the expansion phase. After how many years is the entire nebula ionized? It can be assumed that the photo-ionization equilibrium is always realized because the expansion time scale is much longer than the ionization/recombination time scale. Check if this is a good approximation.

Problem 2: Interstellar extinction

This exercise should illustrate that there are "good" and "bad" wavelength regions for the observation of objects which are attenuated by interstellar absorption along the line of sight. The interstellar extinction is dominated in the UV, visual, and IR wavelengths by the interstellar dust. In the far-UV, below 91nm, the extinction is due to the ionization of neutral hydrogen atoms. The extinction from the Sun to the Galactic Center is in the visual band (V-Band: 0.55 μm) $A_V = 25$ mag. It is assumed that the extinction is homogeneous along the line of sight.

a. How large is the extinction in the K-band in the near infrared at 2.2 μm adopting the "universal" relation $A_K = 0.465 \cdot E_{B-V}$ for dust?

b. How large is this extinction expressed in optical depths τ_V and τ_K for the V- and the K-Band?

c. Calculate from the interstellar extinction to the Galactic Center the mean hydrogen density along the line of sight, using the relation $N_H \approx 6 \cdot 10^{21} E_{B-V} \mathrm{mag}^{-1} \mathrm{cm}^{-2}$ and a distance of 8 kpc.

d. A nearby B0-star at 30 pc can be observed with a far-UV satellite at 90nm, but it's flux is attenuated by a factor of 1000 due to the photo-ionization of H I along the line of sight. Compute the average ionization degree $N(\mathrm{H}^+)/N(\mathrm{H}^0)$ for the line of sight. (Use the hydrogen density $N(\mathrm{H}^+) + N(\mathrm{H}^0) = 2\,\mathrm{cm}^{-3}$ and the H I absorption cross section $a_\nu(90\text{ nm}) = 5 \cdot 10^{-18}\ \mathrm{cm}^2$).