Star Formation – HW #6

Due Friday December 14. Answer the following questions. Show all work.

1. **Waiting for the dust to settle ...**

In this problem we will consider the timescales for dust settling and spatial distribution for different sized silicate dust grains.

(a) Consider particles with $s = 0.1$ and $10\ \mu$m located at $r = 1$ AU in a MMSN disk, where $z = h$, the disk scale height. Assume the disk has radius of 40 AU and the star mass is $M_* = 1 M_\odot$. Estimate the Reynolds number and determine whether Epstein or Stokes drag applies for each particle size.

(b) Find an expression for the terminal velocity of small dust grains with radius s as a function of position z in the disk. Estimate this velocity for the 0.1 and 10 μm particles described above.

(c) Assuming a vertically isothermal disk, show that the settling time can be expressed as

$$t_{\rm settle} = \frac{2\Sigma}{\pi \rho_m s \Omega} e^{-z^2/2h^2}, \tag{1}$$

where Σ is the disk surface density and ρ_m is the dust density. Compute the settling time for 0.1 and 10 μm dust grains at $z = h$ and compare these values to other relevant timescales.

(d) Now let's consider a turbulent (alpha) disk. Derive an expression for the minimum value of α required to prohibit settling on a scale of $z = h$. Calculate the value of α for $s = 0.1$ and 10 μm. If $\alpha = 10^{-2}$ for an accreting protoplanetary disk, for what grain sizes is settling efficient? Discuss the implications of this result.

(e) Consider the dust particles as a separate fluid with density, ρ_d, suspended in a disk with density ρ and subject to the competing influence of settling and turbulent diffusion. Assuming the dimensionless friction time Ωt_{fric} is independent of z, show that their steady-state density distribution can be described by

$$\frac{\rho_d}{\rho} = \left(\frac{\rho_d}{\rho}\right)_0 e^{-z^2/(2h_d^2)}, \tag{2}$$

where h_d is the dust scale height,

$$h_d = \sqrt{\frac{\alpha c_s^2 \rho c_s}{\Omega^3 \rho_m s}}. \tag{3}$$

2. **Cooking up complex chemistry.**

In this problem you will model the astrochemistry of a protoplanetary disk using the Nahoon gas-grain astrochemistry code. You can download the latest version here: *http://kida.obs.u-bordeaux1.fr/codes.html*. Use the KIDA 2014 reaction network that is contained in the download. Note, the package includes IDL routines for reading and plotting the abundances; you can use these or create your own version in python.

(a) Modify the input parameter file to model gas with $\rho = 2 \times 10^{10}$ g cm^{-3}, $T = 10$ K, CRIR $= 1.3 \times 10^{-17}$ s^{-1}, $s = 10^{-5}$ cm Silicate grains. Produce plots of the abundance ratios HC_3N/HCN and CH_3CN/HCN as a function of time. Explain any trends with time. Do your results agree with those of Oberg et al. (2015)? Why or why not?

(b) Vary the gas temperature and dust size separately over several orders of magnitude. What impact does this variation have on the HCN, HC_3N, and CH_3CN abundances and the abundance ratios in (a)? Does this agree with your expectations and why?

(c) The CRIR may be a couple orders of magnitude lower than the "fiducial" Galactic value in the disk midplane due to attenuation (e.g., Cleeves et al. 2014). Meanwhile the CRIR may be an order of magnitude higher at the disk surface due to CR accelerated in accretion shocks (Gaches & Offner 2018b). Vary this parameter over several orders of magnitude. What effect does this have on the abundances and level of agreement with the ratios reported by Oberg et al.?

(d) Pick another species included in the chemical network that you think is interesting or important for understanding protoplanetary disks. Explore its abundance over a range of different physical conditions. Justify your choice of species (why should it be interesting) and report the result of your numerical experiments (e.g., for what times and parameters is the abundance the highest, lowest etc).