Problem Set 2 v2
ISM/IGM G6002y_2024
Issued: 02/29/24
Due: 03/17/24

Name:
Collaborated with:

Dust, Molecules, PDRs and Warm-Hot Gas: Some Calculations, some Cloudy

As in PS1, you will need to have a working version of Cloudy (c23.01).

It is fine to collaborate in groups, but turn in your problem set (answers, code and plots) individually.

1. **Circumstellar dust**

An optically thin circumstellar envelope of constant dust mass, extending from r_{min} to r_{max}, is illuminated by a central stellar source. Consider two different 'density laws' for the envelope:

- Constant density throughout the envelope
- A steady-state (constant mass loss rate and constant velocity) wind density profile $n(r)=n_0(r/r_0)^{-2}$ where n_0 is the density at some fiducial radius r_0. (Consider: Why does the wind produce this profile?)

A) How will the peak temperature of the dusty envelope (in total luminosity) differ between these two cases?

B) How might you expect this temperature to vary for envelopes surrounding a carbon star (such as CW Leo) and stars producing an oxygen-rich envelope?

Be as quantitative as possible. (for B, assume source has same spectrum as ISRF)

To answer this, you can modify the steady state grain temperature equation in PIIM (24.18) for a spherical shell illuminated by a central point source, and consider the total luminosity to result from a composite of multiple spherical shells producing dust emission in the IR.

C) Based on your results above, what might determine the r_{min} of the dusty circumstellar envelope? (e.g. how will T_{peak} vary vs. r?)

D) Lastly, if the envelope is not optically thin in the UV-visible (due to dust absorption), how will this modify your results?

2. **Dark Cloud vs. PDR Chemistry and Cloud-Building Timescales**

In class we discussed the processes and molecular networks responsible for generating several of the most abundant molecular species, including H_2, CO and OH.

An initially neutral, atomic (gas phase) cloud with $n_H=10^{3.5}$ cm^{-3}, T=30 K, and standard ISM abundances and dust-to-gas ratio, is in a photon-dark region (e.g. $A_V>5$). The cloud is exposed to a standard Galactic CR ionization rate.

A) How long will it take for H_2 to form, assuming no photo-dissociations are occurring during this time period? (Calculate approximate formation timescale, no need to solve diff. eq. for $n(H_2)$ fraction.)

B) Assume all hydrogen is now molecular. Using any other simplifications, how long will it take CO to form in this dark cloud? How long will it take OH to form? What ion is important for driving the C and O chemistry of dark clouds? Explain your assumptions in deriving this timescale reactions and rate-limiting step. What reaction or reactions might be rate-limiting? (As part of this, you may need to assume an electron number density, which you can approximate as equal to the number density of the dominant ion.)

C) How do the above timescales compare to the cloud free-fall time (e.g. PIIM eq 41.19), assuming that the cloud is self-gravitating?

D) Two key differences between a dark cloud and a PDR are i) the presence of singly-ionized C^+ with $n(C^+) \sim n(C)$ and ii) the fact that CO can be easily photo-dissociated in these regions (making these regions "CO-dark"). What molecules may be produced as a result of abundant C^+ chemistry that can serve as unique tracers of PDR regions (as opposed to dark clouds)? Where have these molecules been observed? (Briefly describe 1-2 such observations, wavelengths and the molecular transition involved, whether rotational, vibrational or electronic.)

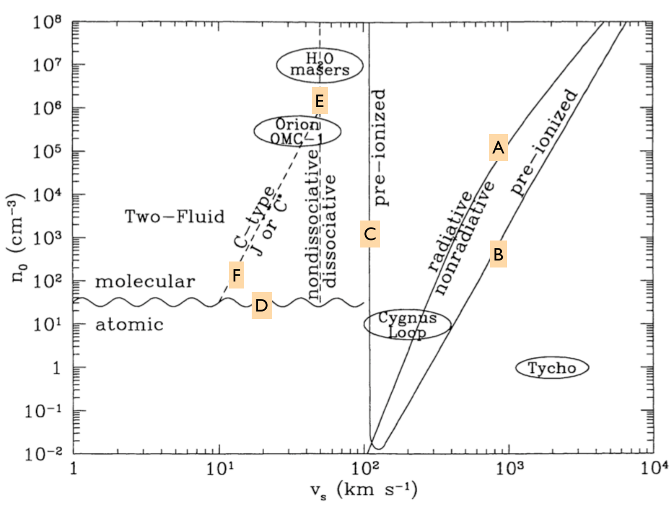
3. Cloudy modeling of PDR and dark regions in various limiting cases

Several cloudy model input files and a Python notebook (G6002y_2024_PS2-PDR-Dark-Cloudy.ipynb) uploaded to Courseworks contains code to model a photodissociation region. We will model an initial 'fiducial' PDR and then also explore how the structure of the PDR changes as we vary several key parameters (density, abundance, CR ionization rate).

A. For the fiducial PDR – how do species ionization and fractions, molecular compositions and temperature vary with Av? In each region (low A_V, high A_V), which processes dominate the heating and cooling rates?

B. How does the PDR structure (species ionization and fractions, molecular composition and temperature) vary as we change the key parameters? Why would these vary in these different limiting cases?

4. Interstellar Shocks



The figure to the left shows a shock-diagnostic plot, found in several papers on "Interstellar Shocks" by McKee and Draine and discussed briefly in lecture. (McKee & Draine 1991, Science 252, 397), paper also uploaded to Courseworks. Explain as precisely as possible each of the curves A-F in the pre-shock density vs. velocity plot. Explain why the curves separate distinct regions in this plane and do your best to explain their shape.