PROBLEM "CLOUDY", ASTRONOMY 216

1. The Problem

Gary Ferland's **cloudy** is a well-developed, freely-available program in wide use by astronomers for calculating the heating, cooling, thermal equilibrium, and spectral properties of interstellar gas. Originally, it was restricted to ionized regions having temperatures $10 \rightarrow 10^8$ K; now it works for molecular, neutral, and partially ionized regions as well. And originally it was Gary's baby; now it's a bigger community. It is freely available, with lots of documentation, at *http://www.nublado.org* . You can download and compile it (C++ compiler) yourself or, alternatively, you can use my copy (see below).

Use this program to calculate the observed spectrum from the gas in an HII region for three cases:

1. An HII region with standard gas abundances and no dust grains.
2. The same HII region with standard gas abundances and standard dust grains.
3. The same HII region with standard gas abundances, except for Oxygen which is twice-enhanced, and no dust grains.

Take the central star as a blackbody with temperature 60000 K and assume the volume density in the HII region is 100 H-nuclei per cm^{-3}. For all cases, plot the spectrum, i.e. the frequency/wavelength dependence of the quantity νF_ν, which is quantity given by **cloudy**. This quantity has the advantage that, when plotted, the height of the graph is proportional to the total power emitted—e.g., for spectral lines, the height of the line is proportionaal to its total power. You may want to plot two or more spectra, concentrating on different frequency ranges. In the optical/UV, it's most appropriate to plot versus wavelength and use the units optical astronomers do, i.e. Angstroms or (if you're James Graham) nanometers. For broader frequency ranges, either frequency or wavelength in microns is probably most appropriate.

For case 1: Apart from Lyα, what are the wavelengths of the half-dozen or so strongest emission lines in the spectrum? What elements/ions produce these lines?

Compare case 2 with case 1. What is most noticeable effect of the grains on the emitted spectrum? (*Hint:* the effect is *very* noticeable. If you aren't struck by this, you aren't plotting a large enough spectral range). How do the grains affect the intensities of the above strongest lines?

Compare case 3 with case 1. With the increased Oxygen abundance, do all of the Oxygen emission lines get stronger, as you might expect?

2. Using Cloudy

You'll need to look at some of the documentation. Get it by downloading veersion C10.00 on the `wiki/DownloadLinks` page of the website. There are three files: `QuickStart.pdf, hazy1.pdf, hazy2.pdf`, all located in `c10.00/docs` . I found it useful to print `Quickstart.pdf` and use it as a tutorial. The other two files are huge (323 and 348 pages). `Cloudy`'s documentation is immense and a bit cryptic.

To set up the HII region file inputs, you can use the planetary nebula example is §2.2 of Quickstart, modifying the star temperature and the volume density appropriately. To set the abundances, see §7.4 of Hazy 1. This also tells how to include grains, and comments that for internal self-consistency, when you include grains (which are made from heavy elements) you should reduce the gas-phase elements appropriately We won't do this because we want to see what the addition of grains does by itself.

You can get all of the info you need from the `out` file. One section of that file contains the spectrum with enough spectral resolution to distinguish the emission lines. That section is default-formatted awkwardly for extracting plottable numbers; you can make it easier by specifying `print line column` in the `in` file. Even then, though, it's easiest to do some editing of the `out` file to isolate the relevant portion has the spectrum. Then you are left with a four-column list that needs to be read and processed to get the right data. I used IDL, the Goddard library[1], and treated the file entries in fixed-format:

```
fmt='A5,F6,A1,F8.3,F9.4'
readfmt, 'edited_outfile', fmt, v10, w10, x10, y10, z10
```

and selected only those lines having an element name and number (easily done with string manipulation procedures in IDL; or manually edit the file), and also `O II`.

Alternatively, you can use the `con` file, which is perhaps more straightforward.

3. Using Cloudy: Computing aspects

You can run `cloudy` if you log into my computer on the astronomy department's computer network: `ssh vermi.berkeley.edu` . Define your environment variable
`CLOUDY_DATA_PATH` as `/usr/local/cloudy`
(in cshell, this is done with `setenv CLOUDY_DATA_PATH ''/usr/local/cloudy''`). Invoke cloudy with the command `/usr/local/cloudy.exe` . For example, if the planetary nebula file is named `pn.in`, then you type

```
/usr/local/cloudy.exe -r pn
```

[1] You can download this library from GSFC website, or from my web page by downloading all of my IDL libraries.