PROBLEM SET 8, ASTRONOMY 216

This first problem (**1**→**4**) is motivated by the snide implication in last week's class that those paragons of scientific integrity, Reach et al, were lowering their otherwise impeccable standards when they derived the H_2 column density by assuming that the total IR emission from dust grains reveals the total N-nucleus column density. So is there another way to detect H_2 in interstellar clouds? Yes, at least in principle!

For every H_2 that photodissociates, ten return to a vibrational level in the ground state by emitting photons in the UV. Lots of these return to excited vibrational levels, so then they emit IR photons upon going back to the ground state. Both are referred to as fluorescence. Are these fluorescent photons detectable?

1. Consider a cloud whose ratio of column densities $\frac{N(H_2)}{n(HI)} \ll 1$. Calculate the approximate total number of UV photons emitted per cm^3 per s. Do the same for the total number of IR photons. Don't worry about how the photons are distributed over the various lines, just calculate the total numbers involved.

Then assume that everything is optically thin (certainly not necessarily true for the UV photons!) and calculate the specific intensity I (recall, for optically thin case, $I = \epsilon L$, where ϵ is the volume emissivity in erg cm^{-2} s^{-1} $ster^{-1}$).

Hint: Assume that the H_2 abundance is in steady state, and remember that about 10% of all excited molecules dissociate. When $\frac{N(H_2)}{n(HI)} \ll 1$, the H_2 rates are limited by the production rate (there are more than enough photons in the incident UV to destroy every H_2 that is formed).

The fluorescence process is initiated by the absorption of a UV photon by the H_2 molecule. Is the number of flourescing photons dependent on the UV radiation intensity? Why or why not?

2. Now take a look at the spectra and published results. IR spectra are in Sternberg (1988 ApJ 332, 400), among other places, and UV spectra in Sternberg (1989 ApJ 347, 863), among other places. For the diffuse clouds that you just treated, the most relevant reference providing published results is Neufeld and Spaans (1996 ApJ 473, 894); if you divide your total photon emissivity up into the relevant spectral regions, you should recover their results to within a factor of two or so. To compare, make sure optical depth is small by comparing with a low $N(HI)$ case; for a typical diffuse cloud, $n(Htot) = 100$ cm^{-3} is appropriate. Note the "Emission-measure-like" dependence.

3. Are the UV lines detectable? Yes! (Martin, Hurwitz, Bowyer 1990 ApJ 354, 220 is the only published detection of which I am aware). Research opportunity: in the last round of NASA Small Explorer Satellites (SMEX) proposals, two UV spectrometers that can detect the UV H_2 fluorescence radiation made it through the first hoop. One of these is Berkeley's SPEAR (copy in 7th floor reading room). Specs of the spectrometer are given in the "Instrument Description" section. For a diffuse interstellar cloud with angular diameter 0.5°, is the UV fluorescence radiation detectable? (The other proposal was Boston University's SPIDR proposal; presumably, when all is

said and done, only one of these will be funded). Estimate the signal/noise of a 1-day integration for a 0.5° cloud having $N(HI) = 10^{20}$ cm^{-2} and $n(Htot) = 100$ cm^{-3}.

In estimating the sensitivity of SPEAR for the H_2 lines, note that the SPEAR sensitivity is given for the intensity of a *single* CIV line in which all its flux is concentrated in a single line. In contrast, the H_2 divides its flux among many (N) lines (see Sternberg 1989 Table 2). Thus each line contains roughly $\frac{1}{N}$ of the total flux, reducing the signal/noise per line by a factor of N for each line; but there are N lines, and thus N independent estimates of the line intensity, which gives you back a factor $\sqrt{N}$.

4. Neufeld and Spaans make a big point about the red lines (see their table 1) being more easily detected than the IR lines. Suppose one uses a wide-angle, fast camera system like McCullough (1997 AJ 113, 2186) used for Hα, with sensitivity ~ 0.2 R (1 R is $\frac{10^6}{4\pi}$ photons cm^{-2} s^{-1} ster^{-1}).

Are the IR lines of the above cloud detectable by such a system? The answer is not obvious because the camera system uses a filter to exclude extraneous continuum and the number of H_2 lines that are included in the filter—and thus the total energy collected from the H_2—depends on the width and center wavelength of this filter. The wider the filter, the more lines, which is good; but the larger the extraneous continuum (some of which comes from airglow), which is bad. So in answering this question, present some numbers and make some intelligent comments. (To really evaluate this you'd have to look into the airglow lines and other matters, which is not expected). Also, read the article and ask whether these lines might be detectable with such an instrument by increasing the integration time, or whatever.

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5. Now we tackle radiative transfer when photon trapping is important. Table 11 of HT (1999 RMP 71, 173) gives FS IR line intensities for five regions. Take the OI 63 μm and the CII 158 μm intensities for the Orion Bar. Assume that the lines come from the same region, and assume that $T_K = 500$ K, as they list for the interclump conditions. Show that the observed line ratio is reasonably consistent with their listed volume density $n(H) = 5 \times 10^4$ cm^{-3} (I get a four-times smaller density; i suspect the reason is that the Orion Bar is seen more-or-less edge on, while I used the escape probability for a slab and the emitted radiation therefrom is for looking through the slab along its normal vector.

Comments: This calculation can be done making reasonable approximations, if you wish. First, the critical densities for the two transitions are widely different; try assuming that one is thermalized.

HT Figure 20 shows that, for the CII line, you can take $\delta V_{FWHM} = 3$ km s^{-1}. This assumes that the line width isn't affected much by saturation (the nonlinear effect of $(1 - e^{-\tau})$ on the line shape), so the CII line can't be too optically thick.

Is this also true for the OI line? If not, given the fact that the OI line is subthermal means that you'll have to use the escape probability!

b. Look at the line profiles in Figure 20. Estimate the central optical depth of the OI line from its line width and compare the results with the optical depth you calculated above. This illustrates the utility of comparing line shapes, and also the inaccuracies involved!

c. What's the H-nuclei column density in this part of the PDR? Given the volume density, what's the length along the line of sight of this part of the PDR?

What's the equivalent extinction in the optical V band? Express in terms of magnitudes and in terms of optical depth.

d. Considering, first, only other lines listed in this table, why is one forced to include clumps? (Read section IV A).

In addition, there are several other observational reasons for requiring clumps. What are they? (Again, read section IV A).