ASTRONOMY 8300 – FALL 2024
Planetary Nebula Project – "Answers"

1.a. Lines identified in the spectrum of PN NGC 6833, and not on the Seyfert list, include a number of H I and He I lines, as well as [Ar III] and [Ar IV] lines (see the attached table). Lines conspicuously absent are high-ionization lines like He II and [Ne V].

1.b. Absorption lines detected are all due to the interstellar medium in our Galaxy: Fe II λ1608, Al II λ1670, Al III λ1854, Fe II λ2344, 2374, 2382, 2586, 2600, Mg II $\lambda\lambda$2796, 2803, and Mg I λ2853.

1.c. There is a noticeable 2200 A trough due to reddening by dust in the interstellar medium. There is a large jump in the continuum at $\lambda < 3646$ A due to the Balmer recombination continuum (the rise from 3750 to 3650 A is due to crowding together of high-order Balmer lines). The continuum at $\lambda > 3750$ A is likely due to the Paschen recombination continuum. The rise in the flux towards the UV may be continuum emission from the central PN star.

2.a.

$$F(H\alpha) = 1.68 \text{ x } 10^{-11} \text{ ergs s}^{-1}\text{cm}^{-2}$$

$$F(H\beta) = 5.14 \text{ x } 10^{-12} \text{ ergs s}^{-1}\text{cm}^{-2}$$

$$\left(\frac{H\alpha}{H\beta}\right)_{obs} = 3.27$$

$$\left(\frac{H\alpha}{H\beta}\right)_{intrinsic} = 2.87 \quad \text{(case B recombination, Ost. Table 4.2)}$$

$$A_\lambda(4861) - A_\lambda(6563) = -2.5\log\left(\frac{2.87}{3.27}\right) = 0.14$$

$$E(B-V) = 0.88\ [A_\lambda(4861) - A_\lambda(6563)] \text{ (from reddening curve)}$$

$$E(B-V) = 0.88\ (0.14) = 0.12$$

2.b. The reddening correction removed the 2200 A dust feature, which is confirmation that the E(B-V) value determined above is approximately correct.

3.a. Emission-line ratios: see attached table

3.b. The temperature-sensitive ratios at low density are:

$$[\text{OIII}]\frac{\lambda 4959 + \lambda 5007}{\lambda 4363} = 80.9, \quad [\text{N II}]\frac{\lambda 6548 + \lambda 6583}{\lambda 5755} = 19.2$$

Rough estimates are obtained for $n_e = 10^4$ cm^{-3} from Osterbrock's equations 5.4 and 5.5 T ([O III]) ~ 13,500 K, T ([N II]) ~ 20,000 K.
These values are discrepant, and a better way to determine T and n_e is given in 3.c.

3.c. The density-sensitive ratios at low density are:

$$\text{[S II]}\frac{\lambda 6716}{\lambda 6731} = 0.4 \pm 0.1, \quad \text{[O II]}\frac{\lambda 3729}{\lambda 3726} = ?$$

Unfortunately, the [O II] lines are blended. However, the centroid of the blend is around 3726 A, which indicates $n_e > 10^3$ cm^{-3}. The [S II] lines are weak and therefore noisy, but this ratio is □0.5, which makes n_e □ 10^4 cm^{-3}.

The [O III] and [N II] ratios in problem 3.b. are somewhat density sensitive, due to the lower critical densities of the levels that give rise to [O III] $\lambda\lambda$4959, 5007 and [N II] $\lambda\lambda$6548, 6583 lines. So we can use these to solve for T and n_e simultaneously. Substituting the observed values into Osterbrock's equations 5.4 and 5.5, we can determine the density as a function of temperature for each, and plot the dependence (see the attached plot). The point at which the two lines cross provides a solution to both equations at:

T = 12625 K, $n_e = 7 \times 10^4$ cm^{-3}.

We will use these values as initial model constraints.

3.d. He II emission is not present, which is somewhat unusual for a planetary nebula. This indicates that there are very few ionizing photons at energies of $h\upsilon > 54$ eV. Thus, NGC 6833 is a low-ionization PN. The lack of other high-ionization lines that require $h\upsilon > 54$ eV photons (e.g., [Ne V]), is confirmation. Also, the lack of Bowen resonance-fluorescence lines (e.g., O III λ3133) is not surprising, since they require He II Lα in order to be produced. Given the lack of photons with $h\upsilon > 54$ eV, the temperature of the central star must be much lower than 100,000 K.

4.a. Given the large number of required and optional input parameters for CLOUDY, it is important to constrain as many as possible before running the code. Given the distance of the PN (4750 pc) and the angular distance from the star (~0.4 arcsec), the maximum distance of the gas from the star is 2.84×10^{16} cm. We will use this as the approximate distance to the ionized face of the cloud. So the initial parameters that we will keep fixed are log radius (cm) = 16.4, log hydrogen density (cm^{-3}) = 4.8. We will also keep an eye on the temperature near the ionized face, since the diagnostic ratios are weighted toward that region. We will match the strong lines, as well as certain weak lines that are important diagnostics.

A series of models were run, as described below. After the initial model, only parameters that were changed from the previous model are listed.

1) PN1: radius 16.4, hden 4.8, blackbody temp=100000 luminosity=38, filling factor 0.3, sphere. This is the standard example, updated for radius and density. It clearly produces too much He II/Hβ (=0.09). [O III] /Hβ (=17) is also too high, so lower the luminosity (which lowers the ionization parameter, since the distance and density are fixed).
2) PN2: lumin=37 – Still produces too much He II/Hβ (=0.10). Clearly, the temperature of the star is too high- it produces too many photons at $h\upsilon > 54$ eV. [O III] /Hβ (=15) only decreased a little.

3) PN3: temp=70,000 - He II/Hβ =0.02, still a little too high. [O III] /Hβ =10, which is getting close. [O II] /Hβ = 0.31, which is too high. So lower the temperature of the star (which should take care of some photons that produce [O III]), but increase the luminosity (to increase the [O III]/[O II] ratio)
4) PN4: temp=60,000 lumin=37.5 – Eureka! We're getting close. He II is down to a very small level (0.006). The strong coolant, [O III], is well matched. Most other strong or diagnostic lines are matched to within a factor of two: [O II], [O I], [N II], C III], and [Ne III]. Note that He I will be matched by just about any model that doesn't have He II, since it's due to recombination, just like the H lines. Also, all the Balmer lines will keep fixed ratios over a wide range of parameters, due to recombination. The only diagnostic lines that are not matched well are the [S II] lines, which are overpredicted by the model. So we will try to trim the column density, since the very low-ionization lines are produced at the back of the cloud.
5) PN5: stop column density 20.9 – Well, this produces the small [S II] values correctly, but [O I] is predicted to be <0.001. Also, this model underpredicts [O II] and [N II], so truncating the column density was not the right thing to do. Since the [S II] λλ6716, 6731 lines have the lowest critical density of all these lines, try increasing the density a little (not too much, or the [O II] and [N II lines will be quenched).
6) PN6: hden 5.1 (no stop column density) – This is it! The [S II] lines are reduced (although still overpredicted a bit), and everything else is still OK. Increasing the density decreased the ionization parameter a little, which brought down [O II] to its observed level. Stop here, and resist any additional fine-tuning!

4.b. The final model is PN6. The model ratios are given in the attached table (boldface gives strong and/or diagnostic ratios). The final parameters were: radius 16.4, hden 5.1, blackbody temp=60000 lumin=37.5, filling factor 0.3, sphere.

4.c. Most lines are well matched by the model. Not sure what's going on with the UV lines of O III] and N III], which are underpredicted. Can't play with the abundances, since the other O and N lines are matched. [S II] is still overpredicted by a factor of ~2, but increasing the density reduces the model values for [O II] λλ3726, 3729 and [N II] λλ6548, 6583. This suggests that there is possibly more than one component, which is not unlikely, given the observational evidence for density inhomogeneities in planetary nebulae. There might be a contribution from higher density clouds, which would suppress the [S II] through de-excitation.

4.d. Most of the line ratios are extremely well matched by a simple model (PN6), which is actually somewhat surprising given the complex structure that we see in nearby PNe. It's interesting that we did not have to change a number of other parameters to get a good match, such as column density and abundances. The model [O III] temperature (10,500 K) is a little lower, and the model density a little higher than our initial values, but the model is approximately correct because we get the right line ratios. A multi-component model would give a better fit, but we resist the temptation since it would add many more free parameters.

Line	$F/F(H\beta)_{obs}$	$F/F(H\beta)_{model}$	Line	$F/F(H\beta)_{obs}$	$F/F(H\beta)_{model}$
O III] λ1663	0.12	0.05	[Ar IV] λ4712	0.012	0.016
N III] λ1750	0.11	0.03	Hβ λ4861	1.000	1.000
C III] λ1909	**0.62**	**0.57**	[O III] λ4959	2.45	2.74
OIII]/CII] λ2324	0.09	0.12	[O III] λ5007	**7.33**	**8.26**
[O II] λ2470	0.09	0.14	[N II] λ5755	**0.018**	**0.018**
He I λ2946	0.013		He I λ5876	**0.16**	**0.14**
He I λ3189	0.023		[O I] λ6300	**0.03**	**0.04**
H 15 λ3712	0.013	0.020	[O I] λ6364	0.009	0.012
[O II] λ3727	**0.13**	**0.09**	[N II] λ6548	0.09	0.06
H 12 λ3750	0.03	0.03	Hα λ6563	**2.87**	**2.86**
H 11 λ3771	0.03	0.04	[N II] λ6583	**0.26**	**0.18**
H 10 λ3798	0.04	0.06	He I λ6677	0.04	0.03
He I λ3820	0.010		[S II] λ6716	**0.002**	**0.005**
H 9 λ3835	0.06	0.08	[S II] λ6731	**0.005**	**0.011**
[Ne III] λ3869	**0.78**	**0.78**	He I λ7065	0.12	0.12
H 8, He I λ3889	0.14	0.13	[Ar III] λ7136	0.12	0.20
Hε [Ne III] λ3970	0.38	0.40	He I λ7281	0.009	
He I λ4027	0.022		[O II] λ7325	0.15	0.18
[S II] λ4072	0.009	0.06	[Ar III] λ7751	0.03	0.05
Hδ λ4100	0.24	0.27			
H γ λ4340	0.45	0.48			
[O III] λ4363	**0.12**	**0.07**			
He I λ4471	0.04	0.05			
He II λ4686	**<0.01**	**0.006**