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Diffuse Nebula Lab

1. Introduction

1.1. Emission-line spectra

Some of the most beautiful objects in the sky are diffuse nebulae, such as star-forming regions (e.g. the Orion Nebula, M42) and planetary nebulae (e.g. the Ring Nebula, M57). Although these phases occur at very different stages in the life-cycle of stars, they share common physical processes that govern their appearance: in both cases, a central hot object (young stars, resp. white dwarfs) irradiate the gas in the nebula with UV photons. These photons are energetic enough to ionize the gas in the nebula. The electrons freed through this photo-ionization carry the excess energy of the absorbed photon over the ionization potential (13.6 eV) as kinetic energy; through collisions with other electrons and ions this energy is distributed, leading to an equilibrium velocity distribution function (a Maxwell distribution) with characteristic temperature T - this is the temperature of the nebula. Collisions between ions and electrons furthermore can excite lower-energy levels of the ions. Ions and electrons recombine, emitting a photon in the process. Usually, recombination takes place to a higher-evergy excited state (rather than the ground state). The atom decays to lower-energy levels down to the ground state, either through emission of a photon, or through collisional de-excitation. Since these transitions correspond to discrete changes in energy (the difference in energy between the two energy levels), the emitted photons have a discrete energy spectrum. The emission of the nebula is thus dominated by certain emission lines, corresponding to the most common line transitions in the nebula. Since the density of these nebulae is much lower than typical laboratory conditions on Earth, even long-lived excited states decay through photon emission (rather than collisional de-excitation), leading to “forbidden” lines not observed on Earth (these lines are marked with square parentheses).

1.2. Temperature measurements from optical line ratios

The higher the temperature of the nebula, the higher the kinetic energy of the free electrons, meaning that higher-energy levels can be populated. It is thus possible to measure the temperature by observing the relative line strengths of transitions between different energy levels of the same ion. Oftentimes, different transitions of the same ions are at very different wavelengths, but a few sets exist where the lines are relatively close, and can thus be easily observed with the same instrumental set-up. One such example is doubly ionized oxygen, O^{++}. Fig. 1 shows the energy-level diagram for the lowest three levels of O^{++}, and explains why the ratio of the 4959Å and 5007Å lines to the 4363Å is sensitive to the gas temperature. Quantitatively,

$$\frac{F[4959] + F[5007]}{F[4363]} = \frac{7.90\ \exp(3.29 \times 10^4/T)}{1 + 4.5 \times 10^{-4}\, n_e\, T^{-1/2}} \tag{1}$$

where $F[\lambda]$ is the flux of the line at wavelength λ, T is the gas temperature (measured in Kelvin), and n_e is the electron density (measured in cm^{-3}). Note that the line ratio is only weakly dependent on electron density, since the typical densities in nebulae are small ($\sim 10^2 - 10^4$cm^{-3}).

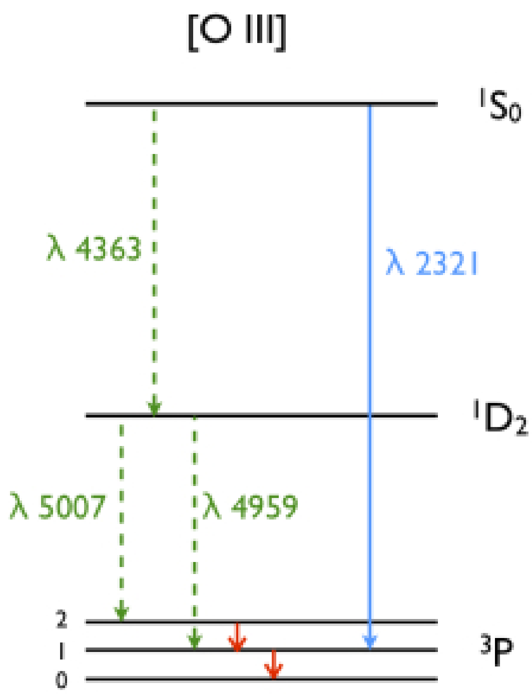

Figure 1. Schematic diagram of the energy levels of O^{++} that lead to the most common [O III] lines. The ^3P level is the ground state; its energy-splitting is exaggerated in the figure. In low-temperature nebulae, only the first energy level, $^1D_2$, is populated; the [O III] emission is thus dominated by the lines at 4959Å and 5007Å. In higher-temperature nebulae, also $^1S_0$ is populated, leading to an emission line at 4363Å. The ratio of the 4959Å and 5007Å lines to the 4363Å line is thus highly sensitive to the gas temperature. Figure adapted from Osterbrock & Ferland (2006).

1.3. Density measurements from optical line ratios

The gas density can be measured by considering the effects of collisional vs. radiative de-excitation on two lines of the same ion that have very similar energy levels. In the limit of $n_e \to 0$, the timescale of collisional de-excitation becomes much larger than the life-time of the excited states; hence, every (collisional) excitation is followed by de-excitation through the emission of photon. The relative line strengths therefore reflect the probability by which the upper energy level is populated, i.e. the relative probabilities of the collisional excitation rates. These scale with the statistical weight of the excited state, i.e. the number of distinct spin states, which determines how many electrons a state can "hold". We here consider two transitions of S^+: $^2D_{5/2} \to^4 S_{3/2}$ and $^2D_{3/2} \to^4 S_{3/2}$, which give rise to emission lines at 6716Å and 6731Å, respectively (see Fig. 2). The $^2D_{5/2}$ level has 6 distinct spin states; the $^2D_{3/2}$ level has 4 distinct states. Hence, in the low-density limit, the line ratio is:

$$\mathrm{F}(6716)/\mathrm{F}(6731) = \frac{n(^2D_{5/2})}{n(^2D_{3/2})} = \frac{6}{4} = 1.5 \quad . \tag{2}$$

In the limit of $n_e \to \infty$, both photo-emission and collisional de-excitation de-populate the excited states. The strength of the emission line therefore scales with the number of available states times the probability per unit time for spontaneous emission, i.e. the Einstein A coefficient of the particular transition. Hence, in the high-density limit, the line ratio is:

$$\mathrm{F}(6716)/\mathrm{F}(6731) = \frac{n(^2D_{5/2}) \cdot A_{^2D_{5/2} \to ^4S_{3/2}}}{n(^2D_{3/2}) \cdot A_{^2D_{3/2} \to ^4S_{3/2}}} = \frac{6}{4} \cdot \frac{2.6 \times 10^{-4}}{8.8 \times 10^{-4}} \simeq 0.44 \quad , \tag{3}$$

for a typical temperature of 10^4 K.

In these limiting regimes, the line ratio is constant; however, in-between, specifically in the range of $n_e \sim 10^2 - 10^4$ cm^{-3}, the line ratio is sensitive to the density, as shown in the right panel of Fig. 2. Since the densities of diffuse nebulae are typically in this range, this line ratio can be used to measure their density.

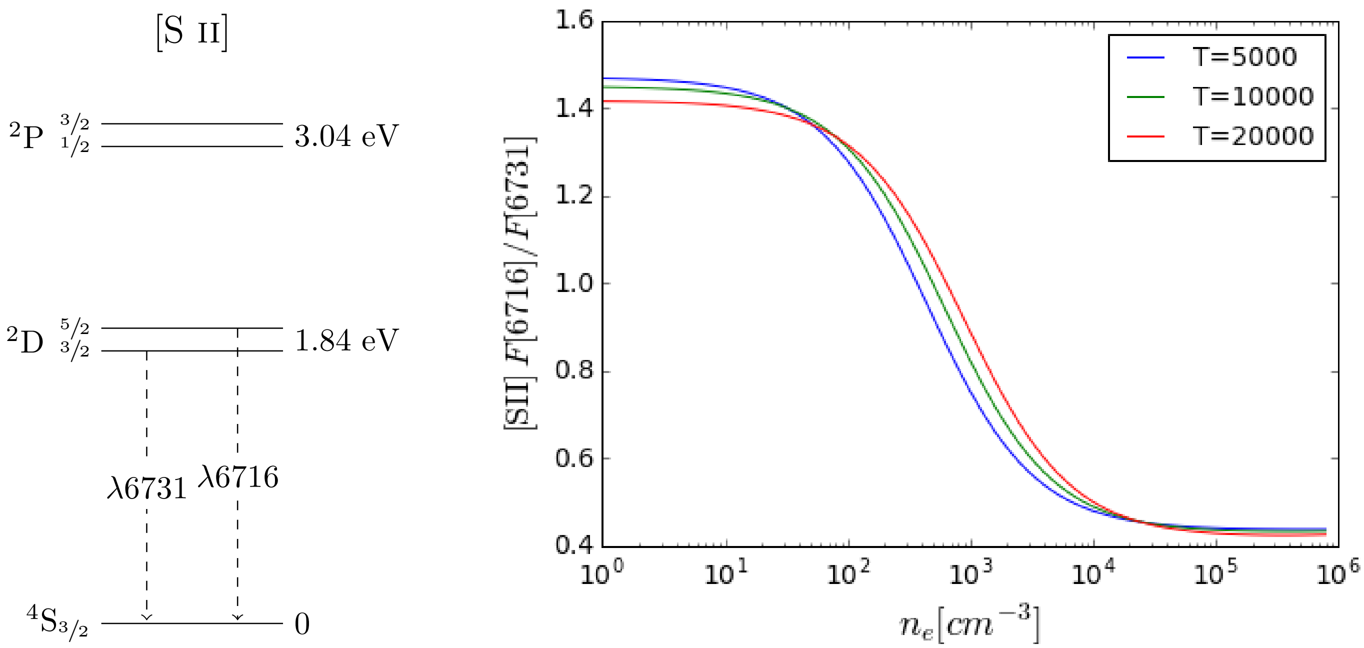

Figure 2. Left: Schematic diagram of the lower-energy levels of S^+. The emission lines at 6716Å and 6731Å correspond to the transitions from $^2D_{5/2}$ resp. $^2D_{3/2}$ to $^4S_{3/2}$. Right: the dependence of the line ratio $\mathrm{F}(6716)/\mathrm{F}(6731)$ on gas density. Figures adapted from Osterbrock & Ferland (2006).

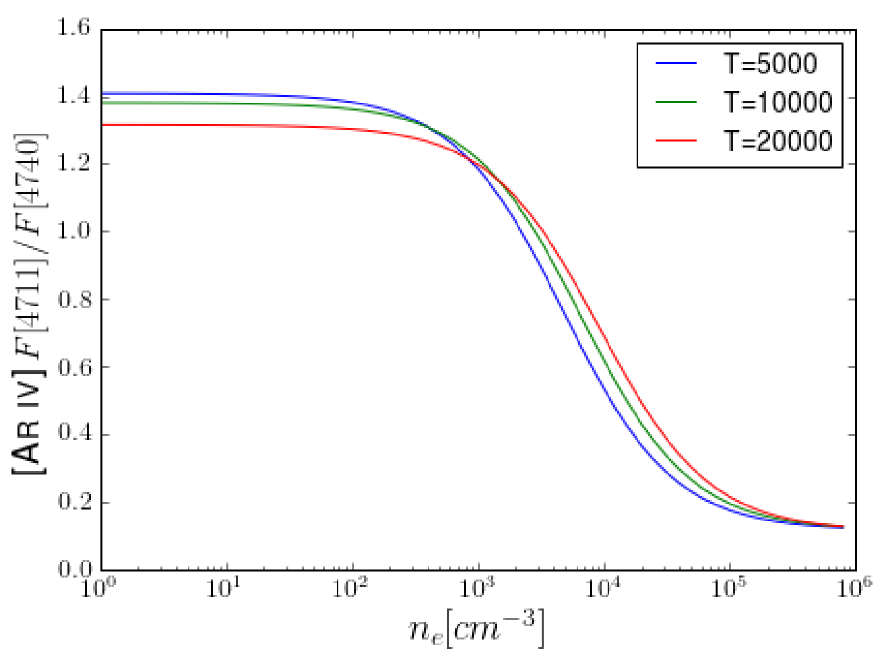

Figure 3. The dependence of the line ratio $\mathrm{F}(4711)/\mathrm{F}(4740)$ on gas density.

A very similar calculation can be done for the ratio of the lines in the [ArIV] doublet at 4711Å and 4740Å, see Fig. 3.

2. Equipment

- "high-resolution" DADOS spectrograph with 900 l/mm grating
- ST402ME CCD camera (NOT the big STL1001 camera)
- Orion StarShooter AutoGuider
- same laptop as for imaging lab

3. Targets

- a high surface brightness diffuse nebula (a star-formation region or a bright planetary nebula)
- a B or A type star brighter than mag 6, within 20 degrees of the target, as spectrophotometric reference star

4. General Strategy

- The overall goal is to measure the temperature and the gas density of a diffuse nebula from the [O III] lines, and the [S II] lines, respectively. Because the spectral range of the spectrograph is about 700 Å, separate observations have to be taken for the two line sets.
- You will aim to observe the following lines:

  - Hγ 4341 Å
  - [O III] 4363 Å
  - HeII 4686 Å
  - [Ar IV] 4711 Å
  - [Ar IV] 4740 Å
  - Hβ 4861 Å
  - [O III] 4959 Å
  - [O III] 5007 Å

  and:

  - [N II] 6548 Å
  - Hα 6563 Å
  - [N II] 6583 Å
  - [S II] 6716 Å
  - [S II] 6731 Å

- To calibrate the sensitivity of the spectrograph as function of wavelength, you will also need to take a spectrum of a bright reference star of type B or A, with the same settings.
- For each wavelength setting, take a spectrum of the Neon and/or Mercury arc lamp for wavelength calibration.
- For each wavelength setting, take a flat-field by pointing at the dome, illuminated by the dome lamps.
- Use autodarks for images of arclamps, standard stars, and flat-fields. Do not use autodarks for your science exposures; instead, take series of dark frames with the appropriate exposure time(s) after your observations.

5. Preparation

- Before the observations, develop a strategy for how to set the grating angle to capture the targeted emission lines. This is especially important for the [O III] (4363, 4959, 5007 Å) lines, since they cover close to the full range of the spectrograph (666Å vs. 700Å). Study the arc lamp spectra to identify which arc lines should fall where on the CCD (e.g. the line at xxxxÅ has to be placed x pixels from the left edge of the CCD) to ensure that all targeted lines, as well as enough of the continuum on either end, are captured. Use the dispersion relation (i.e. the number of Å per pixel) that you determined in Lab 0.
- Print finder charts for your target. The FOV of the spectrograph is small (only a few arcminutes). Make sure to bring a finder chart for the finder scope, as well.

6. Data acquisition steps

See separate document.

7. Data reduction steps

See separate document for details.

1. Correct for the dark current. To do so, create a master dark at each exposure time and subtract it from the corresponding spectra.
2. For each wavelength bracket, do the following:
   (a) Flat-field the data.
   (b) Extract the 1D spectrum of the nebula. You might be able to combine the 2d spectra before collapsing to 1d; or you can extract a 1d spectrum from each exposure and then combine those (how?).
   (c) Find the dispersion relation (the pixel to wavelength mapping) from the arc lamp spectrum.
   (d) Identify the emission lines of the nebula. If your arc lines only cover part of the wavelength range, use the nebular lines to improve your wavelength calibration.
   (e) Extract the spectrum of the standard star and use it to derive the sensitivity function for each setting.
   (f) Apply the sensitivity function to the spectrum of the nebula.

8. Data analysis

- Identify which lines you can detect. Measure the emission line fluxes. Did you detect any lines not listed here? If so, try to determine what they are by comparing to the literature.
- Determine the gas temperature from the [O III] lines, according to Eq. 1. Assume a typical density of 10^3 cm^{-3}.
- Determine the electron density of the gas from the [S II] lines. The simplest way to do so is to read off the value from Fig. 2.
- Revise your measurement of the gas temperature, if necessary.
- Compare your measurements to results reported in the literature. Are they consistent? If not, what might be the reasons?

9. Lab report

This lab report is to be handed in as a pdf generated from a jupyter notebook. Make sure to use markdown boxes to motivate and describe your analysis (it should not be necessary to read the code to try to understand what you did.) Name the file as `123456789_Lab3_w_123456789.pdf`, replacing the first number with your SBU ID, and the second with that/those of your lab partner(s). E-mail the report to the instructor (only).

The timeline for the lab report, and intermediate check-ins is the following:

+1 week: Prepare the extracted, wavelength-calibrated, and exposure-averaged spectrum for each wavelength setting.

+2 weeks: Derive the sensitivity functions and the flux-calibrated spectrum of the nebula. Also send in a table of measured emission line strengths.

+3 weeks: Report your estimates of line ratios, gas temperature and density, as well as the comparison to literature-reported values. Present an initial assessment / interpretation of any discrepancies.

+4 weeks: Hand in your lab report.

Bonus Task

You were instructed to include the Hγ line in your observations. Calculate the ratio of Hγ to Hβ. What does the result tell you? How does it affect your measurements of the temperature and density?

REFERENCES

Osterbrock, D. E., & Ferland, G. J. 2006, Astrophysics of gaseous nebulae and active galactic nuclei