H II regions and massive star formation

Spring 2024

H II regions are clouds of ionized gas surrounding O stars, associated with molecular clouds. The gas is ionized by ultraviolet light from these massive young stars, recently formed from molecular clouds. Large fractions of the gas in H II regions can be found in high ionization states, such as N^{++}, O^{++}, Ne^{++}, and S^{++}, as well as lower ionization-potential species. Among the diffuse nebulae that are prominent near the plane of the Milky Way, we distinguish H II regions from a few other kinds of nebulae. Planetary nebulae are the most H II region-like: their gas is photoionized by the hot core of a dying star that has shed most of its cooler outer layers. The average degree of ionization is usually higher in planetary nebulae than in H II regions. In contrast, supernova remnants (SNR) and Herbig-Haro (HH) objects are lower in ionization state overall: they rarely show ions besides hydrogen and singly-ionized species, such as N^+, O^+, and S^+. We understand these latter objects to receive their ionization from kinetic energy of flows of material that encounter their surroundings supersonically: the supernova blast in the case of SNR, and high-speed outflows from young stellar objects in the case of HH objects. Together, these objects form a set of sign posts of star formation and star death for high- and low-mass stars: H II regions and supernova remnants for the birth and death of massive stars; HH objects and planetary nebulae for the birth and death of lower-mass stars.

Not that any of this was obvious. The brightest H II region in the sky, M42, is visible to the naked eye and was known to the ancients; that it contained ionized hydrogen became clear in the latter half of the nineteenth century. But the composition of H II regions, and their role in the cosmic scheme of things, remained obscure until the 1920s. Then, in rapid succession: Edwin Hubble showed that visible H II regions are always associated with O stars (Hubble 1922a, Hubble 1922b); Ira Bowen identified the brightest lines in these nebula, formerly ascribed to "nebulium," to forbidden lines of ions like O^{++}, Ne^{++}, and S^{++} (Bowen 1927, Bowen 1928); and Herman Zanstra showed that ultraviolet photoionization followed by recombination gave a good account of the hydrogen recombinations lines, also providing a way to estimate the effective temperature of the star responsible for the ultraviolet light from the nebular emission (Zanstra 1927, Zanstra 1928, Zanstra 1931 [1]).

After this, the study of star formation could begin in physical earnest. In this project, we will follow the footsteps of Hubble, Bowen, and Zanstra in particular, to determine certain ionic abundances in H II regions. From this, we will determine the effective temperature of the ultraviolet spectrum and compare this to the properties of the candidates among the stars that could be providing this ionizing radiation. For good measure, we will also see how to identify the signs of lower-mass star formation in the same neighborhood as H II regions, signs that were not recognized for a couple more decades.

In this project, you will:

- Observe a small selection of bright, nearby H II regions, including the complex in Orion's sword, M 42 and M 43. Make other selections among the wintertime[2] H II regions, which are displayed in TheSkyX. Make sure that you pick real H II regions and not reflection nebulae. Besides

[1] In German. If you do not read German, it is probably easier to look up "Zanstra temperature" in a textbook like that by Osterbrock & Ferland (2006). If you do, please translate it for us.

[2] Star formation regions, being close to the Milky Way, spend the night close to the horizon around the equinoxes and are, by the same token, highest in the sky around the solstices.

M 42/M 43, we recommend NGC 2024 in Orion's belt and NGC 2264 in Monoceros. The number of observable HII regions drops off dramatically around the middle of the semester and does not increase again for months, so plan to observe at your first opportunity.

To increase the S/N in your final images, you are welcome (and encouraged) to combine your observations with those taken in earlier years. Previously observed HII regions include:

- M42: 2022 (Jan. 27; Feb. 7, 15; Mar. 4, 8, 17), 2023 (Feb. 8, 11; Mar. 15)
- NGC 896 (IC 1805): 2022 (Mar. 3, 10)
- NGC 2024: 2022 (Feb. 18), 2023 (Feb. 8, Mar. 15)
- NGC 2174: 2022 (Mar. 4, 16)
- NGC 2264: 2022 (Feb. 18, 21)

- Take high signal-to-noise images in the spectral lines of Hβ, [OIII], Hα, and [SII]; and in L, for help in assembling a nice composite false-color image.
- As usual, average the data in each filter, omitting frames with tracking errors or unusually bad seeing.
- Measure and account for the line-intensity limit in each filter.
- Carefully edit the data for bad stellar images; prepare flux-calibrated images in each of the four spectral lines. Recall that the [SII] filter includes two similarly-bright [SII] lines, at wavelengths 6717Å and 6731Å. By [SII], we will mean the total flux in the filter, which is the sum of the two line fluxes.
- Make an image of foreground extinction, A_V, from the Hα/Hβ image ratio. Assume Case B recombination, for which the Balmer decrement is $(\mathrm{H}\alpha/\mathrm{H}\beta)_{A_V=0} = 2.86$.[3]
- Use this image to correct your images for extinction. As you do, arrange to not display pixels for which the S/N of either line in the pair is less than about 5. Use the interstellar extinction curve by O'Donnell (1994) with the ratio of total to selective extinction $R_V = A_V/E(B-V) = 5$.
- Deconvolve the L images; prepare flux-calibrated images in the four spectral lines; and prepare composite L-[OIII]-Hα-[SII] images, both extinction-corrected and not, in your favorite tricolor scheme.
- Prepare extinction-corrected line flux ratio images: [OIII]/Hα, [SII]/Hα, and [SII]/[OIII]. As you do, arrange to not display plxels for which the S/N of either line in the pair is less than about 5.

Be sure to address the following in your analysis:[3]

- Do your images reach the line-flux sensitivity limit you expect? If not, why not? What are the random and systematic uncertainties of the fluxes and flux ratios that you derive?
- What systematic trends do you see in the extinction? Describe the relation between the HII regions and nearby dusty molecular clouds, seen via their extinction.
- Consider the intensity of the lines that you detect, and the lateral extent on the sky of the line emission. What is each object's depth (along the line of sight) of the line emission region likely to be? Is the object more like a sphere or a blister?
- What are the typical values of the ionic abundance ratios $\chi_{\mathrm{O}^{++}} = \frac{n(\mathrm{O}^{++})}{n(\mathrm{H})}$ and $\chi_{\mathrm{S}^{+}} = \frac{n(\mathrm{S}^{+})}{n(\mathrm{H})}$ in the various distinct regions of these nebulae? What are the fractions of O and S in these ionization states? How are these abundance ratios distributed relative to the bright stars

[3]See the long-form HII region lesson for equations involving intensities of recombination and forbidden lines, and for the relevant atomic-physical parameters of HI, [OIII], and [SII].

within each HII region? Take the elemental abundance ratios to be $\frac{\mathrm{O}}{\mathrm{H}} = 3.3 \times 10^{-4}$ and $\frac{\mathrm{S}}{\mathrm{H}} = 1.0 \times 10^{-5}$, use the simplest reasonable approximations and justify these approximations.

- What would be the effect of taking the electron density to be $n_e = 5000\ \mathrm{cm}^{-3}$ instead of the "simplest reasonable" approximation assumed above?
- From your Hα image, what is the Zanstra effective temperature of the radiation field that ionizes each nebula?
- The ionization potentials of S and O^+ are 10.4 eV and 35.1 eV, respectively. If the nebulae absorb all the light at these energies and higher, and if we may approximate the temperature of an O star with a blackbody, what is the temperature of the O star that ionizes each nebula?
- How do these last two temperatures compare to the properties of OB stars in these nebulae, based on their spectral types?
- Based on the luminosity and surroundings of these stars, how old are they likely to be, and how much longer are they likely to live?
- In $\frac{[\mathrm{SII}]}{[\mathrm{OIII}]}$ line-ratio images of your nebulae, you will note some regions and compact objects with particularly large values of this ratio. What are these regions likely to be?
- **Extra credit.** If you know how to use an ionization/spectral synthesis code such as Cloudy, use it to fit your line intensities, yielding estimates of the electron density and temperature of selected spots within each of your HII regions. How do the electron densities compare to the critical collision-deexcitation electron densities for [OIII] and [SII]?

Include with your report your best images and plots. Archive these images, and all of your raw and reduced data, on the Mees analysis workstation.

Additional reading

Astronomy 142, lecture 12–14

Astronomy 244/444, lesson 5 and the HII region long form

Osterbrock, D.E. & Ferland, G.J. 2006, *Astrophysics of gaseous nebulae and active galactic nuclei*, second edition (Sausalito: University Science Books), chapters 3–5.