Herbig-Haro objects and low-mass star formation

Herbig-Haro (HH) objects are compact emission-line nebulae associated with associations of young stars, but are not (usually) coincident with individual stars. Examples were first identified in a low spectral resolution, objective-prism survey for emission-line stars, by Guillermo Haro (1950). Haro noticed emission-line objects in his plates that, because they have only faint continuum emission and include bright forbidden lines, are clearly not stars. He passed his observations on to George Herbig for higher-resolution spectroscopic followup. Herbig, in turn, found (1951) that the emission lines represent a large range of ion excitation: neutral O up to O^{++}, for example. Also, emission by low ionization-potential species – like N^{+}, O, O^{+}, and S^{+}– is quite a bit brighter than that by higher ionization species such as O^{++}, Ne^{++}, and S^{++}. This is radically different from spatially-resolved photoionized nebulae such as H II regions, and from the young supernova remnants for which spectra were known at the time. Initially, Herbig favored an explanation for the emission based on the interaction of a wind from a K or M dwarf star with its interstellar surroundings, an explanation that Don Osterbrock pursued in more detail several years later (1958). Several of the first HH objects have bow-wake structures suggestive of outflows. But no HH object was seen particularly close a star that could plausibly serve as the source of the wind. Thus more attention, including Herbig's and Haro's, was paid to the possibility that these objects represent a pre-stellar stage of evolution: star formation caught in the act. This suggestion was consistent with the apparent rarity of the objects – only 42 known by 1978 – and the short time scale for gravitational collapse.

All this changed in a span of just a few years. Inspired by the similarity of recent spectra of HH 1 in Orion, and nebulosity[1] closely adjacent to the young emission-line star T Tauri, to the spectrum of a "mature" supernova remnant[2], Dick Schwartz demonstrated (1975) that the former two are well explained by radiation from stellar-wind-driven shocks with speed $V \approx 100 \text{ km sec}^{-1}$ and preshock, hydrogen-atom number density $n_{\rm H} \approx 10^2 \text{ cm}^{-3}$. Soon thereafter, Herbig and his students (1979, 1981) followed up an earlier observation by Luytens to show, with high astrometric precision and accuracy, that several HH objects have large proper motions, corresponding to velocities of hundreds of km sec^{-1} in the plane of the sky; and that, furthermore, the proper motions trace back to individual, heavily extinguished stars revealed in infrared surveys (e.g. 1974). At much the same time, bipolar molecular outflows, also apparently driven by winds from these stars, were discovered to envelope distributions of HH objects (e.g. 1980).

Today there are thousands of HH objects known. Each is clearly associated with a young star deeply embedded within its parent molecular cloud, and with a bipolar molecular outflow. Their study is a key part of the physics of star formation: bearing on the development of young stars by accretion from their surrounding disks, and on feedback in the interaction of young stars with their birth environment. In this project we will observe spectral line emission from HH objects and investigate the excitation of the emission, mostly following reasoning similar to Schwartz's.

In this project, you will:

- observe a selection of bright, nearby HH objects. These should be selected from the wintertime[3] low-serial-number HH objects listed, for example, in this catalogue. HH 1 and 2 in Orion near NGC 1999, HH 5 through 12 in Perseus near NGC 1333, and HH 28 and 29 in Taurus within L1551, are highly recommended but must be observed early in the semester. If you must wait til late in the semester, consider the HH objects in Monoceros: HH 39 north of R Mon and NGC 2261, and HH

[1] Called Burnham's Nebula, and not to be confused with Hind's Variable Nebula (NGC 1555) nearby.

[2] N49, in the Large Magellanic Cloud. By 1975, supernova remnants of this stage of development were well explained as emission from shocks driven in the interstellar medium by the supernova's blast wave.

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

124, 125, 226, and 226 between the center of NGC 2264 and the Cone Nebula. Be warned that they are fainter than the others, though. Observe at your first opportunity.

- take high signal-to-noise images in the spectral lines Hβ, [O III], Hα, and [S II]; 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 detection limit in each filter.
- carefully edit the data for bad stellar images; prepare flux-calibrated images in each of the three spectral-line filters. Recall that the [S II] filter includes two similarly-bright [S II] lines, at wavelengths 671.7 nm and 673.1 nm. By [S II] 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 the Balmer decrement is $\left(\mathrm{H\alpha/H\beta}\right)_{A_V=0} = 4.0$, rather than the Case B value 2.86. [4]
- use this image, suitably masked, to correct your images for extinction. As you do, arrange not to display pixels for which the signal-to-noise ratio of either line in the pair is less than about 5. Use the interstellar extinction curve by Weingartner & Draine (2001), with ratio of total to selective extinction $R_V = A_V/E(B-V) = 5$.
- identify the HH objects in your images, and in ds9 define apertures encompassing each distinct part, also measuring fluxes of the four spectral lines in each aperture, both extinction corrected and not.
- deconvolve the L images and prepare composite L-[O III]-Hα-[S II] images, both extinction corrected and not, in your favorite tricolor scheme.
- prepare line flux ratio images, [O III]/Hβ and [S II]/Hα, both extinction corrected and not. As you do, arrange not to display pixels for which the signal-to-noise ratio of either line in the pair is less than about 5.

In your analysis, answer the following questions:

- 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 you derive?
- What systematic trends do you see in the extinction toward the HH objects? In particular, is there a correlation between extinction and projected distance from a nearby star that could plausibly be an outflow source?
- Raga, Böhm & Cantó (1996) introduced an excitation scale for HH objects, which corresponds to these flux ratio ranges:

High excitation	[O III]/Hβ ≥ 0.1	[S II]/Hα < 1.5
Intermediate excitation	[O III]/Hβ < 0.1	[S II]/Hα < 1.5
Low excitation	[O III]/Hβ < 0.1	[S II]/Hα ≥ 1.5

What is the excitation classification of each of your HH object components?

- How much difference does it make to the excitation classifications to have made the extinction correction? Compare the extinction classification with, and without, correction for extinction.

[4] For the HH objects you will consider, collisional excitation of the upper states of Hα, H n = 3, is not negligible, as it is in most other cases in the interstellar medium. A Balmer decrement of 4 is a compromise value; it will usually lie in the range 4-5, not approaching the Case B value except for the fastest shocks.

Use the extinction-corrected images in the following.

- Is it possible for the HH objects to be photoionized? Make this assumption, and answer these questions to see: [5]
  - From your $H\alpha$ fluxes, 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 stellar spectrum with a blackbody, what is the effective temperature of the star that ionizes each nebula? Take the element abundance ratios to have the standard interstellar values, $\mathrm{O/H} = 3.3\times10^{-4}$ and $\mathrm{S/H} = 1.0\times10^{-5}$.
  - What would be the luminosity and magnitude of such a star, were it within the HH object?
  - Is it possible such a star is there?
  - So is it possible that the HH objects can be photoionized?

- Is it possible for the HH objects to be stellar-outflow-driven shocks? Make this assumption, and answer these questions to see: [5]
  - Suppose the temperature of the emission region is $T = 10^4$ K, which would make H recombination lines maximally bright (recall A stars). Suppose further that cold outflowing hydrogen, with density n_H and speed *V*, is brought to rest supersonically – i.e. in a shock – ionizing the flow and turning its kinetic energy to heat. What is the value of *V*?
  - Ejection speeds in celestial mechanics tend to be similar to escape speeds. Is your value of *V* reasonable as an ejection speed from the vicinity of a low-mass (K or M) star, and reasonable for an outflow the star drives in some way? Would large proper motion of your HH objects change this judgment?
  - In Case B recombination, $H\beta$ and $H\alpha$ comprise about 60% of the total flux of all the hydrogen recombination lines. Take the sum of the $H\beta$ and $H\alpha$ fluxes, divided by 0.6, to provide a lower limit to the total rate at which the emitting gas *cools* itself. Suppose that this gas is *heated* at the same rate, and that this is determined by the rate that atoms, moving past the shock front, deposit their kinetic energy. Make reasonable assumptions about the 3-D shapes of the HH objects. What is the mass flow rate, in $M_\odot$ year^{-1}, which would keep the HH objects at steady temperatures?
  - Suppose this is mass lost by a nearby young stellar system. Is this a plausible mass-loss rate?
  - Is there a star nearby which could plausibly be the source of such an outflow?
  - So is it possible that HH objects are outflow-driven shocks?

  Presuming in the following that your answers to the final questions about photoionization and shock excitation are No and Yes…

- Consider the shapes and distribution of the HH objects in your images. Does it seem likely that the outflow is mostly heating small dense clumps of interstellar gas, or that it is interacting with a more uniform medium? Does it seem likely that each HH object may be an "interstellar bullet" spat out from the young stellar system: that is, that the outflow is quite unsteady?
- How would an HH object move around in the Raga et al. excitation scale, with variation in the shock speed *V* and the (preshock) outflow density n_H?

[5] See the long-form H II region lesson for equations involving intensities of recombination and forbidden lines, and for the relevant atomic-physical parameters of H I, [O III], and [S II].

- What is the cooling time scale, in years, for your HH objects? Would you expect their emission to be significantly variable over the span of years?
- **Extra credit.** If you know how to use a shock code, such as MAPPINGS V: what does this code give for the preshock density and shock speed that best fits the line fluxes for your HH objects? What caveats are there for this, regarding unknowns like element abundance, or the detailed geometry of the shock front?

Include with your report your best images and plots. Archive these images, and all of your raw and reduced data, on the Astronomy Lab data drive.

Additional reading

Astronomy 142, Lectures 12, 13, and 14.

Astronomy 244/444, Lesson 5 and the H II Region Long Form lesson.