Herbig-Haro objects and low-mass star formation

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Hergib-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 seen in a low spectral resolution, objective-prism survey for emission-line *stars*, by Guillermo Haro (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 onto George Herbig for higher-resolution spectroscopic follow-up. Herbig, in turn, found (Herbig 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 HII 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 (Osterbrock 1958). Several of the first HH objects have bow-wake structures that would favor the suspicion of outflows. But no HH object was seen close enough to a star that would 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 (Schwartz 1975) that the former two are well explained by radiation from stellar-wind-driven shocks with speed $V \approx 100$ km/s and preshock, hydrogen-atom number density $n_H \approx 10^2$ cm^{-3}. Soon thereafter, Herbig and his students (Cudworth & Herbig 1979, Herbig & Jones 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/s 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., Strom et al. 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. Snell et al. 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 with their birth environment. In this project, you will observe spectral line emission from HH objects and investigate the excitation of the emission, mostly following reasoning similar to Schwartz's.

[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.

In this project, you will:

- Observe a selection of bright, nearby HH objects. These should be selected from the winter-time[3] low-serial-number HH objects listed, for example, in this catalog. 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 until late in the semester, consider the HH objects in Monoceros: HH 39 north of R Mon and NGC 2261, and HH 125, 125, 126, 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, [OIII], Hα, and [SII]; and in L, for help in assembling a nice composite false-color image.
- 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 the four spectral-line filters. Recall that the [SII] filter includes two similarly-bright [SII] lines, at wavelengths 6717Å and 6731Å. By [SII], we mean the total flux in the filter, which is the sum of these 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 $(\mathrm{H}\alpha/\mathrm{H}\beta)_{A_V=0} = 2.86$.[4]
- Use this image, suitably masked, 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 $R_V = A_V/E(B-V) = 5$.
- Identify the HH objects in your images, and, in SAOImage 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-[OIII]-Hα-[SII] images, both extinction corrected and not, in your favorite tricolor scheme.
- Prepare line flux ratio images, [OIII]/Hβ and [SII]/Hα, both extinction corrected and not. As you do, arrange to not display pixels for which the S/N of either line in the pair is less than about 5.

Be sure to answer the following questions in your analysis:

- Do your images reach the line-flux sensitivity limit that 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 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:

[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.

[4] 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].

Excitation level	[OIII]/Hβ	[SII]/Hα
High	≥ 0.1	< 1.5
Intermediate	< 0.1	< 1.5
Low	< 0.1	≥ 1.5

What is the excitation classification for 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.

Use the extinction-corrected images in the following:

- Is it possible for the HH objects to be photoionized? Make this assumption, and answer each of these questions to see:[4]
  - From your Hα 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 standard interstellar values, $O/H = 3.3 \times 10^{-4}$ and $S/H = 1.0 \times 10^{-5}$.
  - What would be the luminosity and magnitude of such a star, were it within the HH object?
  - Is it possible that 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:[4]
  - Suppose that the temperature of the emission region is $T = 10^4$ K, which would make the H recombination lines maximally bright (recall A stars). Suppose further that cold outflowing hydrogen, with density $n_{\rm H}$ 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 larger proper motion of your HH objects change this judgment?
  - In Case B recombination, Hβ and Hα comprise about 60% of the total flux of all of the hydrogen recombination lines. Take the sum of the Hβ and Hα 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 3D shapes of the HH objects. What is the mass flow rate, in $M_\odot$/yr, that would keep the HH objects at steady temperatures?
  - Suppose that 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 that your answers to the last two questions about photoionization and shock excitation are No and Yes…

- Consider the shapes and distributions 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 might be an "interstellar bullet" ejected 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, if the shock speed V and the (preshock) outflow density n_{H} varies?
- What is the cooling timescale, 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 Mees analysis workstation.

Additional reading

Astronomy 142: lectures 12–14

Astronomy 244/444: lecture 5 and the H II 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.

