Photoionized Herbig-Haro objects in the Orion Nebula through deep high-spectral resolution spectroscopy

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Herbig-Haro objects (HHs), named for their discoverers, George Herbig and Guillermo Haro, are small nebular regions originated from gas ejections from newly formed stars. Since the early 50s, many of these objects have been observed in neutral environments where their optical emission stands out from the surrounding gas. In these cases, the optical spectrum is dominated by shock heating, a process that excites and ionises the gas using the kinetic energy of the jet. This heating is followed by a cooling of the gas through the emission of Recombination Lines (RLs) and Collisional Excited Lines (CELs). HHs are also present in the nebulae where stars are born, that is, HII regions. In these cases, the intense radiation field emitted by the O- and B-type stars is capable of photoionising the surrounding gas, which reaches an equilibrium set by the global physical conditions of electron density and temperature ($n_{\rm e}, T_{\rm e}$).

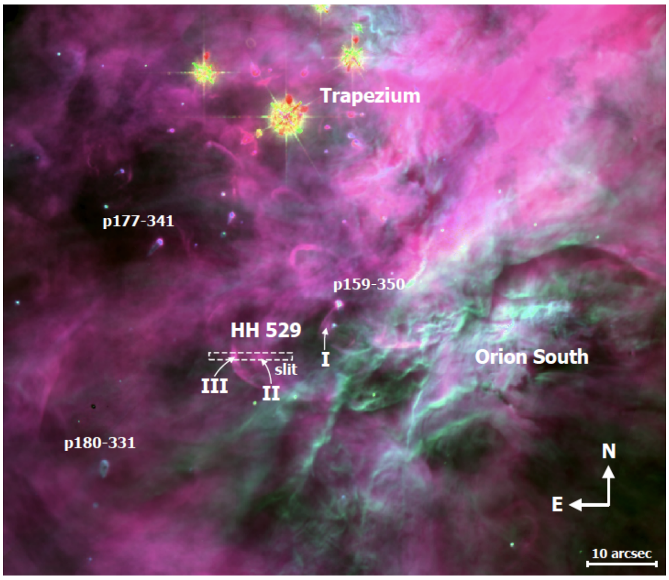

Figure 1: Image of the central area of the Orion Nebula taken with the WFPC2 of the HST [1] using 3 filters: F502N, F658N, and F656N for colors red, green, and blue, respectively. The three most prominent bow shocks of the Herbig-Haro object HH529 are indicated. Image taken from [3], indicating the slit position of the spectroscopic observations.

The Orion Nebula, the brightest HII region in the night sky, is home to a significant number of HHs. Several of these objects are photoionised by the intense radiation field of the Orion Trapezium stars, particularly from the θ^1 Ori C star. This radiation dominates over the shock-heating and fix a photoionisation equilibrium in these HHs, so their emission spectra become analogous to those of small-scale HII regions.

The great variety of morphologies, velocities and distances with respect to θ^1 Ori C covered by these HHs allows us to study the chemical composition of the Orion Nebula, which is representative of the Solar neighbourhood, under different conditions of density and degree of ionisation. In addition, it allows us to investigate the impact that shocks have on the destruction of dust grains. Through deep observations of these HHs with high spectral resolution spectroscopy, we can separate their Doppler-shifted emission from the optical radiation of the Orion Nebula and study them individually.

HH529II-III

HH529 is an HH object located in the central zone of the Orion Nebula as is shown in Figure 1. Its three most prominent bow shocks, named HH529I, HH529II, and HH529III, indicate its eastward propagation. We [3] analysed HH529II and HH529III through deep optical spectra taken with the UVES spectrograph at the Very Large Telescope (VLT) and 20 years of images from the Hubble Space Telescope (HST).

The emission spectra of these objects indicate that they are composed of fully photoionised gas, mainly from intermediate and high ionisation species (ions with ionisation potentials, IPs > 25 eV). The compression of the gas in the bow shocks of HH529 increases their electron density, reaching values of $n_{\rm e} \sim 30\,000$ cm^{-3} in HH529III, up to a factor 5 higher than the density of the Orion Nebula in the same line of sight. Due to their high degree of ionisation, it is possible to estimate the total abundances of He, C, O, Cl, Ar and Fe without Ionisation Correction Factors (ICFs), which are relationships based on photoionisation models used to consider the contribution of non-observed ions in the optical range to the total abundance.

Multiple RLs from heavy elements as O^{2+}, C^{2+} or Ne^{2+} were detected in HH529II and HH529III, which are several orders of magnitude weaker than the CELs of the same ions. This allowed to explore the Abundance Discrepancy problem (AD problem), which is the systematic difference between the ionic abundances obtained with the intensity of RLs and CELs. The AD problem may indicate the existence of physical phenomena not well understood such as temperature inhomogeneities, fluorescent excitation processes, chemical inhomogeneities, etc. The different temperature determinations available in HH529II and HH529III suggests that the possible existence of small temperature fluctuations is not enough to explain the observed Abundance Discrepancy Factor (ADF) between the O^{2+} and Ne^{2+} ionic determinations based on RLs and CELs.

A slight overabundance of the heavy elements O, Ar, Ne, S, and Cl (~ 0.12 dex), with a possible origin in inclusions of H-deficient gas, is found in HH529. In addition, there is direct evidence that the shock between HH529 and the Orion Nebula is able to destroy dust grains with Fe content. HH529II shows and abundance of Fe by a factor ~ 2.35 higher than what is found in the Orion Nebula in the same line of sight. The efficiency of the dust destruction may be related to the velocity propagation of HH529, which is ~ -70 kms^{-1} in the reference frame of the Orion Molecular Cloud (OMC), propagating at an angle of $\sim 58°$ with respect to the plane of the sky [3].

HH204

HH204 is an HH object located in the southeast of the Orion Bar, close to θ^2 Ori A in the plane of the sky, as shown in Figure 2. For HH204, we [4] used the same kind of observations as in HH529II-III.

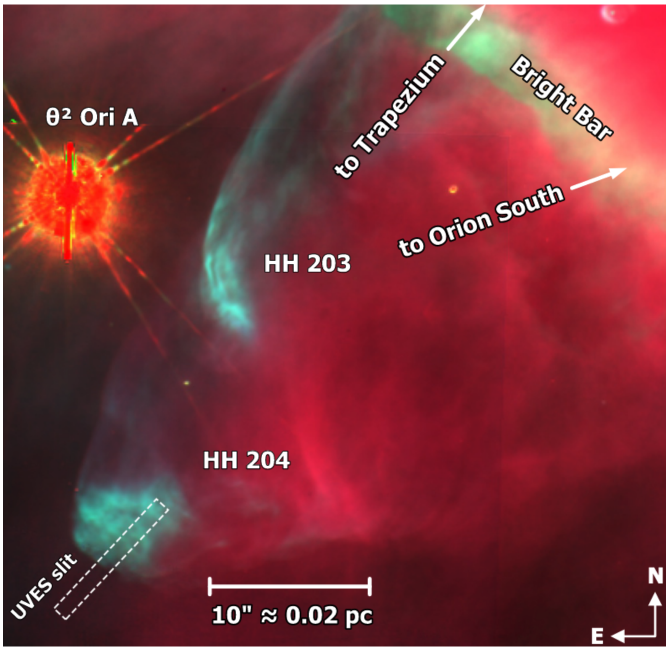

Figure 2: Image of the Orion Nebula in the southeast of the Orion bar taken with the HST WFPC2 [2] using the same color scale as Figure 1. Image taken from [4], indicating the location of the UVES spectrograph slit.

In contrast to the ionisation conditions of HH529II-III, HH204 is mainly composed of low- and intermediate ionisation species (IPs<25 eV) with strong emissions from neutral elements such as O^0 or N^0. This allowed to estimate the abundances of O, N, S, Cl, Fe and Ni without ICF. In addition, it was shown that Fe and Ni have similar depletion and ionisation patterns, presenting abundances a factor 3.5 higher than in the Orion Nebula. This supports the hypothesis that the velocity of propagation of the jet is a key factor in the degree of dust destruction, since HH204 propagates at ~ -90 km s^{-1}, faster than HH529II and HH529III, with a propagation angle of $\sim 32°$ with respect to the plane of the sky.

In this object, the abundance of O presents zero ADF, that is, the abundances obtained with RLs and CELs match. Some clues found in HH204 that can help to solve the AD problem in ionised nebulae are the following: (i) there are no relevant temperature fluctuations in HH204, (ii) the effects of starlight fluorescence in the O I RLs are plausibly negligible for this HH and (iii) no errors in physical conditions or chemical inhomogeneities are expected in HH204.

Finally, we [4] showed that some density diagnostics, commonly used in the study of the interstellar medium –such as [S II] $I(\lambda6716)/I(\lambda6731)$– can underestimate the true density in an integrated spectrum when a high-density inclusion (such as an HH object) is present. This could lead to an overestimation of the true gas temperature, implying wrong estimates of chemical abundances.

Future work

Through the analysis of data of further HHs (such as HH514, HH203, HH202, HH625 and HH518) we seek to explore the relationships between the level of dust destruction, degree of ionisation of the gas, velocity of the jet propagation and distance from the ionizing source. We also seek to determine more precisely the actual chemical composition of the solar neighborhood and constrain the AD problem.

References

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Short CV

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