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The Homunculus: a Unique Astrophysical Laboratory

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ABSTRACT

η Car is surrounded by bipolar shells, the Homunculus and the internal Little Homunculus, that are observed in both emission and absorption. Thin disks, located between the bipolar lobes, include the very bright Weigelt blobs and the neutral emission structure called the Strontium filament. All are affected by changes in UV and X-Ray flux of the binary system. For example, the normally ionized Little Homunculus recombines during the few month long spectroscopic minimum and then reionizes. Spectral data, obtained with *Hubble Space Telescope*/ Space Telescope Imaging Spectrograph (*HST*/STIS) and with *Very Large Telescope*/ UltraViolet Echelle Spectrograph (*VLT*/UVES), provide a wealth of information on spectroscopic properties of neutral and singly-ionized metals and on chemistry of nitrogen rich, carbon, oxygen poor, dense, warm gas. This information is important to understand gamma ray bursters (GRB) that reveal red-shifted near-UV metallic absorptions from pre-GRB stellar ejecta.

1. Introduction

The high spatial resolution of *HST*, combined with appropriate spectral resolutions of the STIS, has been utilized to: 1) Pull out the geometry of the expanding bi-lobed structures. Based upon the infrared emission from the Homunculus and a 100:1 gas-to-dust ratio, the Homunculus, a neutral, dusty hourglass-shaped shell ejected in the 1840s, has at least 10 $M_\odot$ of material (Smith et al. 2003). 2) Discover the Little Homunculus, an internal ionized, bipolar shell associated with an event in the 1890s. 3) Separate of the stellar spectrum from the very bright narrow-lined emission Weigelt blobs located $0''.1$–$0''.3$ from the star. 4) Discover the Strontium Filament, an unusual neutral emission nebulosity, photoexcited by radiation filtered by Fe II (<7.9eV). 5) Characterize temporal variations of these structures

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imposed by the binary interaction of massive stars and their winds.

The 5.54-year periodicity of η Car was first noted by Damineli (1996) through the time variability of [Ne III], [Ar III], He I narrow nebular emission lines. This led to monitoring of the object with the *Rossi X-Ray Timing Explorer* (Corcoran 2005) and coordinated observations with, for example, *HST*/STIS and *VLT*/UVES . The evidence abounds that η Car is a massive binary system composed of a 15,000 K/100 $M_\odot$ primary stars and a 35,000K secondary star. The hot companion is in a highly elliptical orbit, penetrating the extended primary star's atmosphere during periastron. For several months, the Lyman radiation from the binary system is trapped. Ejecta will during this short period of time recombine and cool. This period is defined as η Car's spectroscopic minimum.

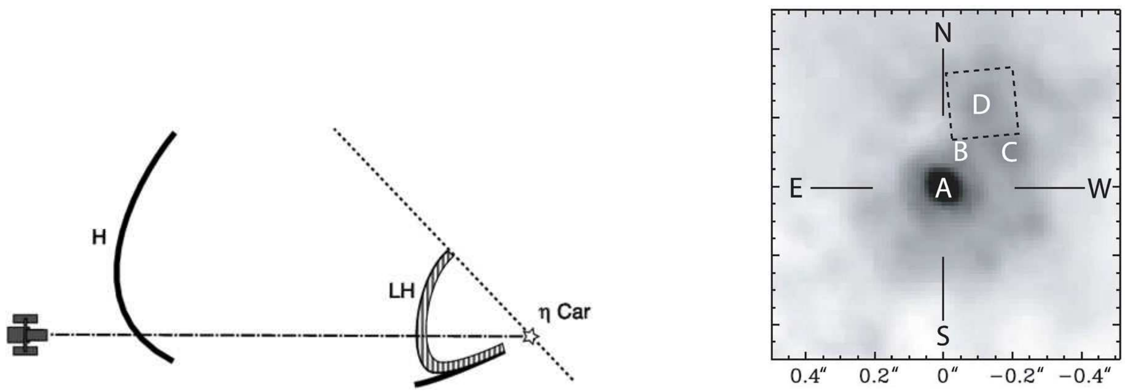

Fig. 1.— Left: We see η Car through two major expanding shells, the Homunculus (H) and the Little Homunculus (LH), that change in ionization and temperature as the UV radiation is modulated by the massive central binary system. Right: The central 1″ region, imaged by *HST*, shows beads on a necklace surrounding the central source. Three beads to the upper right, labeled B, C, and D, are the bright emission line Weigelt blobs.

2. Abundances

International Ultraviolet Explorer and ground based observations in the 1980s (Davidson et al. 1986) demonstrated an overabundance of nitrogen and helium. More recently, Meynet & Maeder (2003) suggested that massive stars late in their CNO-cycle, due to mixing, tend to have an overabundance in nitrogen, while carbon and oxygen are nearly 100-fold depleted. Analysis of the Weigelt blob spectra (Verner, Bruhweiler & Gull 2005) confirmed this abundance pattern. Recently, Bautista et al. (2006) found that Ti/Ni is 80×solar for the Strontium Filament.

Near and Far UV STIS echelle observations have revealed thousands of narrow absorption lines originating in the expanding bipolar shells. Spectra of molecules, neutral and singly ionized iron-group elements at velocity -513 km s^{-1} are associated with the Homunculus. Its level populations correspond to thermal temperatures of 760 K and a density $>10^6$ cm^{-3}.

Spectral lines in mainly singly ionized iron-group elements at -146 km s^{-1} are associated with the Little Homunculus and characterize a 6400 K gas with a density of 10^{6-8} cm^{-3}.

3. The Astrophysical Laboratory

The nitrogen rich, carbon, oxygen poor ejecta are unique. We know their origin, their source of excitation, and have a means of measuring temperatures and modeling densities. Observations with the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) (Iping et al. 2005) and *HST*/STIS (Hillier et al. 2006), leading up to the 2003.5 spectroscopic minimum, confirmed the disappearance of FUV radiation. The -146 km s^{-1} (Little Homunculus) Fe II level populations dropped from 6400 K to 5000 K, then nine months later returned to 6400 K. Strong Ti II absorptions (IP 13.58eV) appeared and disappeared confirming Lyman continuum interruption (Gull et al. 2006). The -513 km s^{-1} (Homunculus) Ti II, and other species, level populations did not change indicating the atomic temperature remained at 760 K. However, the nearly 1000 H2 absorptions extending up to 1600 Å (Nielsen et al. 2006) abruptly disappeared, the much weaker CH and OH absorptions weakened. CH and OH level populations are consistent with 60K (Verner et al. 2005), and H_2 temperatures appear to be about 150 K (N.Smith, priv comm). Recent high-dispersion visible and IR GRB spectra (Chen et al. 2005; Prochaska et al. 2006) revealed multiple lines of Fe II originating from warm circum-protoGRB gas. Temperatures similar to those measured in the Homunculus were derived. While very different abundances and chemistry, the analog of η Car ejecta will provide much insight to protoGRB environments.

Oxygen and carbon are grossly deficient leading to many metals being trapped in gaseous phase as they cannot form oxides. Further evidence indicates that the ejecta dust is composed of silicates and alumina. Given the metals trapped in gas phase, we suggest that the gas-to-dust ratio is significantly greater than 100, which leads to an even greater mass loss estimate. Metal abundances in the ejecta and models of environments with chemical composition observed in the η Car ejecta, are needed.

4. Conclusion

Much is to be learned about ejecta of massive stars, especially in the late stages of the CNO-cycle. The major changes in excitation by the UV fluxes of η Car provide insight to the physics of this circumstellar gas. Testing the models provides feedback to atomic spectroscopy, especially wavelengths, relative transition probabilites and metastable level lifetimes measurable in this astrophysical laboratory: η Car's ejecta.

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