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HST IMAGING OF THE WIND-BLOWN LOBE NGC 6165

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RESUMEN

Observaciones con la cámara de gran campo, WFC, del lóbulo de NGC 6165 han resuelto condensaciones que están siendo fotoevaporadas por la radiación ultravioleta intensa proveniente de HD 148937, además de los efectos erosivos del fuerte viento estelar. El objeto central es una estrella masiva joven superluminosa que se cree está perdiendo masa a medida que desciende hacia la secuencia principal. El análisis más detallado de varias de estas condensaciones indica la presencia de choques fuertes entre el gas fotoevaporado de la condensación y el propio viento estelar. Los tamaños típicos de las condensaciones son cercanos a 10^{17} cm. Los cálculos de las tasas de flujo de masa y las propiedades de la dinámica del gas de estos flujos, revelan que el comportamiento de la condensación es semejante al de una estructura cometaria. Se discuten los mecanismos de eyección provenientes de la estrella central en relación a la morfología observada en la nebulosa.

ABSTRACT

WFC observations of the lobe NGC 6165 have resolved clumps that are being photoevaporated by the intense UV radiation from HD 148937, in addition to the erosive effects of the strong stellar wind. The central object is a massive superluminous young star that is thought to be undergoing mass loss as it descends onto the main sequence. Analysis of several of these clumps in more detail indicates the presence of strong shocks between the photoevaporated gas from the clump and the stellar wind itself. Typical sizes of the clumps appear to be around 10^{17} cm. Calculations are made of the mass flow rates and of the gasdynamic properties of the flows, revealing that the clump is behaving much like a cometary structure. Ejection mechanisms from the central star are discussed with regard to the observed morphology of the nebula.

Key words: **HYDRODYNAMICS — STARS: MASS LOSS**

1. INTRODUCTION

There have been three papers that have focussed in some detail on this object in the past 15 years (Bruhweiler et al. 1981 (BGHC); Leitherer & Chavarria 1987 (LC); and Dufour et al. 1988 (DPH)). As part of these studies, and earlier work referenced therein, it was concluded that the central star HD 148937 was

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responsible for a causal interconnection between the star, the inner nebulosities NGC 6164/5, the faint filaments, and the outer HII region complex associated with the star.

The star itself is thought to be quite massive (40 $M_\odot$, Maeder 1981) and young, thought to be descending onto the main sequence and undergoing the mass loss to achieve stability. Although originally described as being PN-like, this type of object is now referred to as a "bipolar nebula". Mass loss estimates range from $2\text{x}10^{-7}$ $M_\odot$/yr derived from UV observations, to $7\text{x}10^{-6}$ $M_\odot$/yr based on Hα (BGHC).

Using spectra, LC showed that the kinematics of the SE lobe NGC 6165, revealed a radial velocity at Hα of around -50 km/sec (NGC 6164 is observed to be expanding at around +10 km/sec), with the FWHM of Hα being around 33 km/sec compared to 20 km/sec for NII. It was suggested that the star occupied a cocoon phase that enshrouded the star in dust from which it emerged 10^5 years ago (the typical age quoted for the object based on expansion velocities). Extinction around the star is observed to be uniform suggesting that local dust condensations are unlikely. A possible explosive phase is suggested by an extension to the filamentary structures in the SE-NW direction shown by LC on the second panel of their Figure 1, indicating that the stellar wind (known to be interacting with the lobes) is also affecting material at much larger range.

2. OBSERVATIONS

As part of an ongoing program to study condensations in planetary nebulae like objects, NGC 6164/5 was chosen because of it's high surface brightness and well known clumpy structure. A single set of Hα frames was taken to ascertain the feasibility of the technique, and to see the improvements in the view of the object using Hubble's better resolution. The resulting 4 WFC frames, successfully mosaiced, are presented in Figure 1 with respect to the overall lobe structure that includes HD 148937 and NGC 6164. Typical linear scales are indicated assuming a distance of 1300 pc to the nebula.

Several condensations are labelled in the figure. The nomenclature adopted here follows that of DPH. The collimation of the material in the main lobe A is clear, with the direction of collimation clearly oriented toward the central star. However, some curvature appears evident on the south-eastern side of the lobe suggesting that the flow may not be mono-directional. Condensations B and C, previously thought to be single structures, are clearly resolved into multiple clumps with striking contrails. All labelled condensations have been spectrally studied before and as a result we have reasonable estimates of the electron densities and temperatures for the material surrounding these objects.

The imagery itself indicates that the clumps are brightest on the edges facing the star, indicating that photoevaporation could be important in the dynamics of the material apparently being ejected. The larger condensation in C as well as the smaller clumps in B all appear to possess vapor trails extending behind them. There is a marked lack of emission immediately behind each clump. A single pixel in these images is equivalent to around 130 AU, making these "clumps" appreciably large on solar system scales.

3. A STUDY OF THE CONDENSATIONS

Prinja et al. 1990 have measured terminal velocities for the stellar winds emanating from massive stars. In their sample they included HD 148937, quoting a terminal velocity of 2285 km/sec (using their erratum) which is typical of higher luminosity classes for that spectral type (quoted as O6.5 f?p for this star). The star is generally held to be very luminous for it's spectral type with surface gravity only just exceeding radiation pressure at the surface (M_V=-6.0 (Humphreys 1978); R = 17 $R_\odot$ using T_{eff} = 37,800 K (LC)).

Use of this velocity combined with the electron densities derived by LC and DPH for the various condensations, allows simple calculations of the expected conditions in the gas flows around the clumps when exposed to the combination of the intense UV field and the strong stellar wind.

Using Figure 2 as a schematic representation of any one of the clumps evident in our imagery, we attempt to explain some features of the observed structure. The basis of the schematic may be applied to any of the condensations in the upper right panel of Figure 1 with the caveat that individual temperatures and densities may vary a little. We adopt values that appear consistent across the lobes, from LC and DPH, of n_e = 1000 cm^{-3}, and T_e = 7500 K. The extraordinarily parallel appearance of the trails of material behind the larger clumps might suggest the presence of a very strong shock. However, reconsideration of the problem of a gas clump exposed to such strong UV radiation while being embedded in a supersonic gasdynamic flow suggests that the trails may merely be the visible tracer of the stripping of material from the exposed limbs of the clump itself.

The emission observed by DPH and LC in their calculations of electron densities and temperatures for the condensations they selected, appears from our imagery to come from the face of the condensations exposed to the stellar radiation. The electron densities were derived by DPH using the [S II] doublet $\lambda\lambda$ 6716+6730, and therefore this emission originates spatially from regions of higher density located closer to the surface of the clump. We use the schematic in Figure 2 for our nomenclature concerning the various regions of interest. Region 1 is the upstream conditions in the stellar wind. Region 2 is the emission region that appears bright in our imagery and that was studied by DPH, and Region 3 is the downstream material evident as streamers in Figure 1.

Balancing the momentum transfer between the photoevaporated gas pressure and the ρv^2 "ram pressure" between regions 1 and 2 (assuming v_2 and P_1 are small) we can derive the upstream gas density.

$$P_2 = n_2 k T_2 = 2.1 \times 10^{-9} erg\ cm^{-3} \tag{1}$$

$$n_1 = 2.4 \times 10^{-2} cm^{-3} \tag{2}$$

In region 2, a sound speed may be derived using the known pressure and density. If we again conserve momentum in the flow from region 2 to region 3, and assume that the pressure in region 3 is negligible, then we may estimate the ratio of the densities between the regions using the observed ratio of emission intensities, since the rate of gas emission is proportional to the square of the local gas density.

$$\rho_1 v_1^2 = \rho_3 v_3^2 \tag{3}$$

$$\frac{I_3}{I_2} = \left(\frac{n_3}{n_2}\right)^2 \sim 0.3 \tag{4}$$

Calculating the mass flow into the interface between regions 1 and 2, and calculating how much mass is coming out through region 3, we can assess the contribution to the flow from the photoevaporation of the clump itself. The cross section for mass input to the larger clump flows is estimated to be 1.1x10^{34} cm^2. We take the streamers to be part of a cylindrical shell extending behind the clump, and estimated their area to be 6x10^{33} cm^2.

$$\text{Mass In} = \rho_1 v_1 A_1 = 1.00 \times 10^{17} g\ sec^{-1} \tag{5}$$

$$\text{Mass Out} = \rho_3 v_3 A_3 = 1.12 \times 10^{19} g\ sec^{-1} \tag{6}$$

If it is assumed that the increase in mass comes from the photoevaporation of hydrogen atoms then this number is equivalent to 6.71x10^{42} atoms/sec coming out through region 3. The luminosity of the star is around 2.1x10^{39} ergs/sec, which if delivered entirely at the Lyman continuum would yield a flux of 4.5x10^{45} photons/sec. This is clearly an unrealistic assumption, but if 0.1% of the luminosity is delivered at the Lyman limit then we can come close to accounting for the observed increase in mass flow purely from photoevaporation of material from the clump. In many respects these objects are behaving as cometary bodies.

In summary, we have derived the following physical conditions around the clumps in NGC 6165:

Gas Property	Region 1	Region 2	Region 3
Gas Pressure (erg cm^{-3})		2.1x10^{-9}	
Density (cm^{-3})	2.4x10^{-2}	2000	1095
Temperature (K)		7500	
Velocity (km sec^{-1})	2285		10.7
Sound Speed (km sec^{-1})		10.2	
Mass Flow (g sec^{-1})	1.00x10^{17}		1.12x10^{19}

These numbers indicate that the stellar wind is highly supersonic producing a strong shock at the interface between the photoevaporated, dense gas from the condensation and the wind flow itself. This gas flow then strips more material from the limb of the condensation to "mass load" the flow, to produce the streamers we see in Figure 1. The illumination of these streamers may be affected by the condensation itself shadowing the flow leaving areas of little or no emission behind the clump.

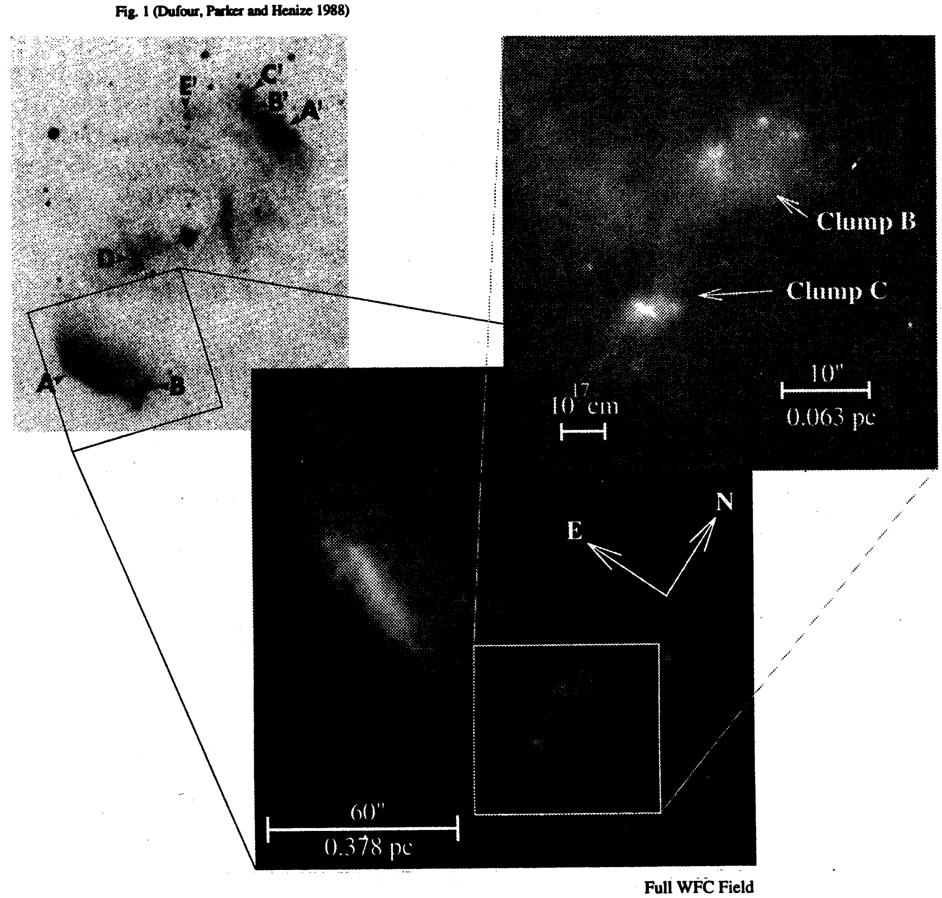

Figure 1: Orientation of WFC field observed relative to overall morphology of the NGC 6164/5 system. Condensations observed by others are labelled using the nomenclature of Dufour et al 1988. Linear scales assume a distance of 1300 pc. Images are displayed using a logarithmic stretch.

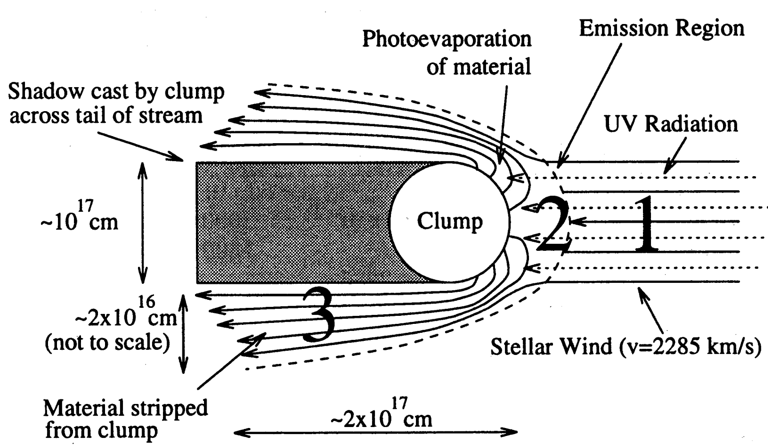

Figure 2: Schematic describing model approach used in text of paper. Three regions studied are labelled as 1, the upstream stellar wind conditions; 2, the emission region just behind the gas dynamic shock; and 3, the downstream evaporated material flow evident as streamers in Figure 1.

4. DISCUSSION OF MATERIAL EJECTION MECHANISMS

A quick look at the overall shape of the nebula NGC 6164/5 reveals the characteristic reverse S-shape that has been noted by most observers about the object. An earlier postulation by Pismis 1974 that an unaligned magnetic field could produce a "garden hose" effect is still a popular and plausible theory. It is not difficult to envision the ejection of material in the manner necessary to recreate the observed structure.

Bipolar ejection of material might be possible from the star if non-radial oscillations were successfully established in the upper atmosphere of the star (Warner 1972). We have already noted that a small potential barrier exists between the bound state of the outer atmosphere and free ejection; it is not difficult to imagine "sloshing" modes causing non-polar ejection of material from the surface. Exactly how this method of ejection would produce such a symmetric pattern of ejecta appears difficult to understand.

If we assume that the Pismis model more closely represents the actual ejection mechanism, and that ejection has for the moment ceased (to account for the faint emission levels from the interior of NGC 6164/5) then the material we observe in the lobes may be moving tangentially as well as radially affording a fortuitous limb-brightened appearance, implying that the general appearance of the system might be quite different if viewed from another angle.

It is clear from our imagery of condensation A that the strong stellar wind is "blowing through" the lobe material leaving clear striations in the gas. What is not apparent is that the proper motion of the lobe may not be purely radial but may possess an azimuthal component due to the rotation of the star (estimated to be fast: v sin(i) around 200 km/sec). Further spectral observations of key regions of the nebula, such as III and IV (D and it's unlabelled antisymmetric counterpart), will be needed to determine the kinematic nature of the nebula. Fabry-Perot observations by Pismis in 1974 did reveal a complex velocity structure that may or may not require a companion to achieve the nutation necessary (Conti, Garmany & Hutchings 1977).

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