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CANDIDATES FOR ABLATED FLOWS

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RESUMEN

Hay evidencias observacionales del cargado de masa de flujos por material arrastrado en una variedad de fenómenos circunestelares e interestelares. En este trabajo evaluaremos la validez de esta evidencia para los flujos observados en las nebulosas planetarias deficientes en hidrógeno A 30 y 78, en los nudos cometarios en la nebulosa de la Hélice, en las "cuerdas" hipersónicas en la nebulosa de Eta Carina, en la cáscara interna de la estrella variable azul luminosa prototípica P Cisne, en la nebulosa del Panal en el halo de 30 Doradus y en los chorros monopolares débiles que provenien de los *proplyds* en M 42.

ABSTRACT

There is observational evidence of the mass loading of flows by ablated material in a variety of circumstellar and interstellar phenomena. Here the strength of this evidence will be evaluated for the flows observed in the hydrogen deficient planetary nebulae A 30 and 78, the cometary knots in the Helix nebula, the hypersonic "strings" in the Eta Carinae nebula, the inner shell of the prototypical luminous blue variable star P Cygni, the Honeycomb nebula in the halo of 30 Doradus, and the weak monopolar jets from the M 42 proplyds.

Key Words: **HYDRODYNAMICS — ISM: JETS AND OUTFLOWS — STARS: WINDS, OUTFLOWS**

1. INTRODUCTION

Two possibilities for the creation of the ablated flows described by Hartquist et al. (1986) and Dyson, Hartquist, & Biro (1993) are shown in Figures 1*a*,*b*. Either the photoevaporated flow of ionized gas from a dense globule mixes with a high-speed, shocked wind, or shocked ambient gas mixes with evaporating material from a hypersonic globule. In both cases, cooler mass is added to the incident flow, which is then both slowed and cooled often to temperatures permitting the emission of optical emission lines. In these circumstances, the ablated flow is detectable with an optical spectrometer such as the Manchester Echelle Spectrometer (MES; Meaburn et al. 1984) now installed on the San Pedro Mártir 2.1 m telescope.

Here, evidence of varying strength from our own observational programmes for the presence of ablated flows in diverse circumstellar and interstellar phenomena will be considered.

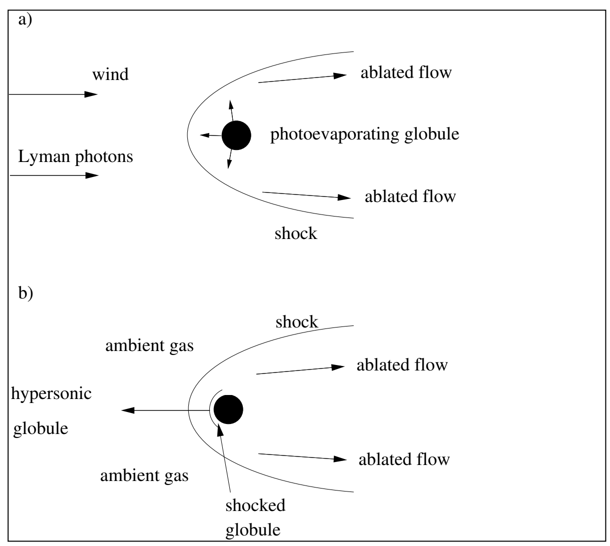

Fig. 1. Two possibilities for the creation of ablated flows are illustrated. (*a*) A particle wind causes an ablated flow from a globule with a photoionized surface. (*b*) Shocked ambient gas mixes with shocked gas evaporating from the surface of a globule traveling at hypersonic speeds.

2. PLANETARY NEBULAE, PNE

The action of ablated flows is almost certainly present in the hydrogen deficient planetary nebulae (PNe) Abell 30 and 78 and possibly in the Helix PN NGC 7293.

2.1. *Hydrogen Deficient PNe—A30 and A78*

The PNe Abell 30 and 78 (Abell 1966) have hydrogen deficient cores within "conventional" hydrogen rich envelopes which are expanding radially at a few tens of km s^{-1}. *Hubble Space Telescope* (*HST*) imagery of the bright core of A 30 revealed cometary

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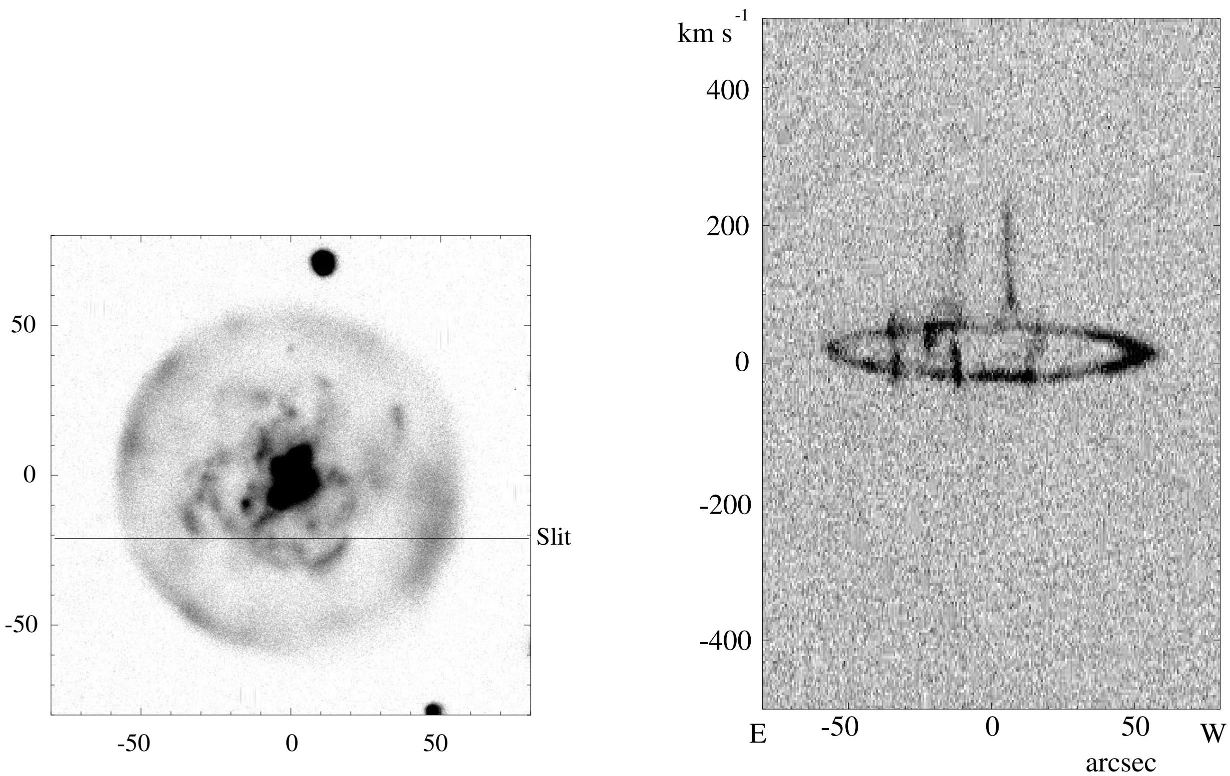

Fig. 2. A slit position is shown across an [O III] 5007 Å image (left panel) of Abell 30. The pv array (right panel) shows both the radial expansion of the hydrogen rich outer shell and velocity spikes over the inner hydrogen-deficient outflows. The radial velocity scale is heliocentric.

shaped flows around the photoionized central knots (Borkowski et al. 1993; Borkowski, Harrington, & Tsvetanov 1995) suggesting ablated flows of the photoevaporated globule material driven by the fast stellar wind from the central star ($V_* = 4000\,\mathrm{km\,s^{-1}}$, $\dot{M}_* = 5 \times 10^{-8} M_\odot\,\mathrm{yr}^{-1}$; Leuenhagen, Koesterke, & Hamann 1993). Velocity "spikes", $200\,\mathrm{km\,s^{-1}}$ in extent, in the position/velocity (pv) arrays of [O III] $\lambda\,5007$ Å line profiles over the edges of the cores of A 30 (Meaburn & López 1996) and A 78 (Meaburn et al. 1998a) must be direct evidence of such ablated flows of the type shown in Fig. 1*a* (see Figure 2 for A 30). *Decelerations* of the ablated flows seem likely to explain (i) the truncation of the velocity "spikes" all at the same radial velocity difference with respect to the nebular cores and (ii) their continuation down to the radial velocity of the system of central knots. The continuous mass loading by evaporated material along the ablated flows would have this effect.

2.2. *The Helix Cometary Knots*

The system of cometary knots surrounding the central star of the Helix (NGC 7293) PN was shown with ground-based imagery (Meaburn et al. 1992) to have dense, dusty, molecular heads ionized on the surfaces pointing towards the star (and see the spectacular *HST* images of O'Dell & Handron 1996). The knots on the nearside of the [O III] $\lambda\,5007$ Å emitting nebular core are silhouetted against this background light and Huggins et al. (1992) detected CO emission from the heads directly. The system of knots was shown (Meaburn et al. 1998b) to be globally expanding within a thick disk at $14\,\mathrm{km\,s^{-1}}$.

Knot 38 in Meaburn et al. (1998b) is by far the most spectacular of these cometary knots, for it is apparently closest to the star yet has the longest tail ($\approx 90''$ long). Furthermore, there is a measured (see Figure 13 of Meaburn et al. 1998b) radial velocity change which implies an acceleration of $22\,\mathrm{km\,s^{-1}}$ along this tail when a reasonable tilt angle to the sky is considered (Figure 3). The expansive velocity at the end of the tail matches closely the $31\,\mathrm{km\,s^{-1}}$ expansion velocity of the CO disk measured by Healey & Huggins (1990).

A direct wind from the central star cannot impinge directly on the system of knots for there is a

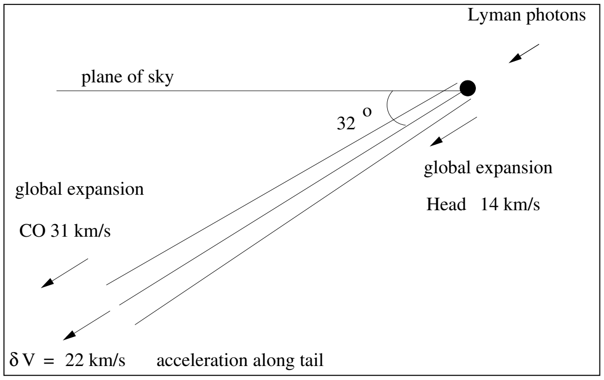

Fig. 3. A schematic model of the Helix cometary Knot 38 which has the longest tail. This tail is tilted at 32 degrees away from the observer and is accelerating along its length. The global expansion of the system of Helix cometary knots is measured as $14\,\mathrm{km\,s^{-1}}$.

central [O III] $\lambda\,5007\,\text{Å}$ emitting shell. One possibility is that any such wind percolates through this central shell, if clumpy, as suggested for RCW 58 by Smith et al. (1984). This fast wind becomes mass-loaded and slowed, before impinging at mildly supersonic speed to again ablate material from the ionized knot heads, which is drawn out to form their long accelerating tails. Otherwise, ablated flows could have formed these tails as the CO emitting shell overran the slower knots. In either case, the flow past the clump is required not to be highly supersonic since such a flow pattern would produce a short stubby tail (Dyson et al. 1993).

3. LBV STARS

The circumstellar environments of both Eta Carinae and P Cygni are rich in the relics of the eruptive events of these luminous blue variable stars. Two phenomena where ablated flows can be invoked for their explanation will be considered.

3.1. *Fingers of Eta Carinae*

The five "fingers" (Meaburn, Wolstencroft, & Walsh 1987; Meaburn et al. 1996; Weis, Duschl, & Chu 1999) of high-speed material protruding through the expanding circumstellar environment of Eta Carinae have characteristics which require distinctly different dynamical explanations to the many other relics of the 1840 outburst. They have between 30 and 100 length-to-thickness ratios (see Finger 1 in Figure 4) and decelerate linearly towards Eta Carinae. Finger 1 has a high-speed ionized knot at its tip (Currie et al. 2000). Redman & Meaburn (2001) and Redman, Meaburn, & Holloway (2002) proposed the model in Figure 5 as one possible explanation.

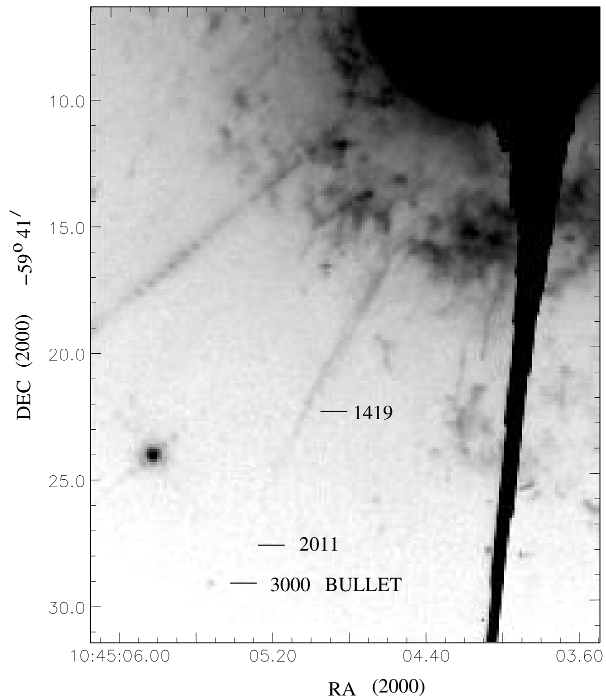

Fig. 4. An *HST* image where Finger 1 is seen projecting from Eta Carinae. The measured outflowing speeds are shown in $\mathrm{km\,s^{-1}}$ at two positions along its length as is that of the "bullet" at its tip. Deceleration towards Eta Carinae could be indicated. The other spikes are diffraction artefacts.

Here a dense, hypersonic bullet, travelling ballistically at $3000\,\mathrm{km\,s^{-1}}$ ploughs through the envelope of ejecta from Eta Carinae to leave a trail of ablated material from its shocked surface (Fig. 1*b*). This trail expands at only the sound speed ($10\,\mathrm{km\,s^{-1}}$—hence its large aspect ratio) and decelerates towards Eta Carinae (Meaburn et al. 1996) as a consequence of the "friction" of oblique shocks. It could be significant that the shocked bullets modeled theoretically by Poludnenko, Frank, & Blackman (2002) are quickly disrupted without forming long tails in similar circumstances. However, more complex models of the bullets themselves need to be explored.

It of course remains possible, but seems more unlikely, that highly collimated jets *accelerating* in random directions away from Eta Carinae could generate the fingers.

3.2. *Inner Shell of P Cygni*

In a series of observations (see Barlow et al. 1994; Meaburn, López, & O'Connor 1999, Meaburn et al. 2000), three distinctly separate circumstellar phenomena of P Cygni have been discovered: these are the 800 yr old inner shell, the 2400 yr old outer shell and a $\geq 10^4$ yr old one-sided giant lobe.

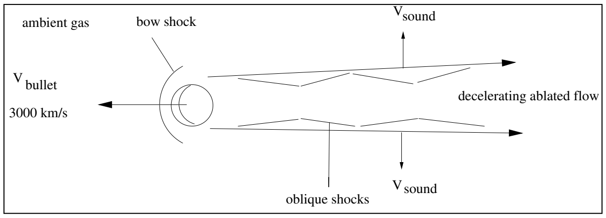

Fig. 5. A model of Finger 1 invoking ablated flows is shown. The finger will have a high aspect ratio for it expands perpendicularly only at the sound speed ($\approx 10\,\mathrm{km\,s^{-1}}$) and will be decelerated towards Eta Carinae by the "friction" of oblique shocks.

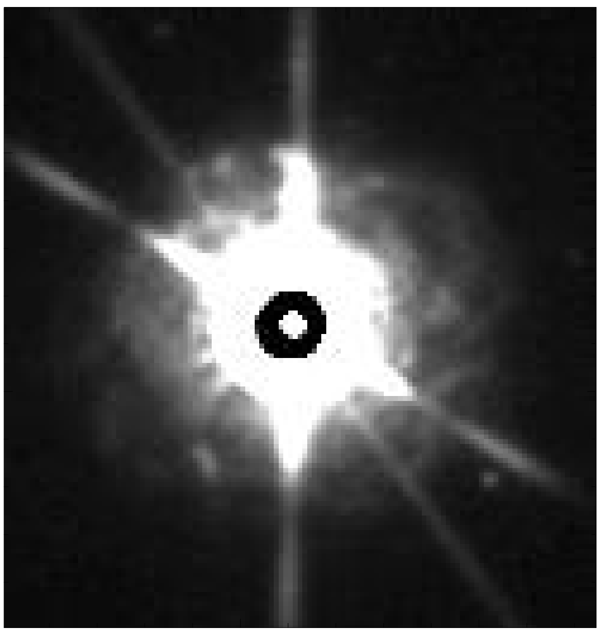

Fig. 6. An [N II] $\lambda\,6584\,\text{Å}$ image of the inner shell of P Cygni. The central star is behind an occulting disk. The spikes are diffraction artefacts.

Velocity ellipses in the pv arrays of [N II] $\lambda\,6584\,\text{Å}$ and fluorescently excited [Ni II] $\lambda\,7412\,\text{Å}$ line profiles over the $23''$ diameter inner shell (Figure 6) indicate spherical expansion velocities of 140 and $110\,\mathrm{km\,s^{-1}}$, respectively. This difference is real and significantly lower that the $206\,\mathrm{km\,s^{-1}}$ (Lamers, Korevaar, & Cassatella 1985) terminal velocity of the particle wind from P Cygni. A reasonable model (Figure 7) has ballistic knots of dense [Ni II] $\lambda\,7412\,\text{Å}$ emitting material travelling outwards at $110\,\mathrm{km\,s^{-1}}$ being overrun by the faster wind. The shocked (or even photoionized) surfaces of these knots mass loads the wind with ablated material to give the [N II] $\lambda\,6584\,\text{Å}$ emission from the $140\,\mathrm{km\,s^{-1}}$ outflowing region.

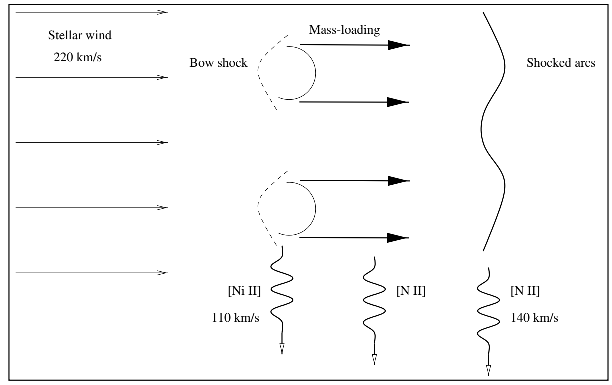

Fig. 7. A model invoking ablated flows to explain the the difference in expansion velocities of the shell of [Ni II] $\lambda\,7412\,\text{Å}$ emitting globules and the [N II] $\lambda\,6584\,\text{Å}$ emitting envelope of the inner shell of P Cygni is shown.

4. H II REGIONS

Ablated flows are invoked as possible explanations of unique kinematical phenomena in both the giant 30 Doradus nebula in the Large Magellanic Cloud (LMC) and the Galactic H II region M 42.

4.1. *The Honeycomb Nebula in 30 Doradus*

The halo of 30 Dor is composed of overlapping 50 to 100 pc diameter giant shells expanding typically at $50\,\mathrm{km\,s^{-1}}$ and with central clusters of hot stars. These giant shells are driven by supernovae and maybe particle winds in their expanding perimeters. Wang (1992) discovered a nebula with a strange honeycomb appearance (Figure 8) in this environment, which was shown to have the X-ray and radio characteristics of a supernova remnant by Chu et al. (1995). Truncated velocity spikes (similar to those in Fig. 2 for A 30) were discovered over the edges of the individual cells in the honeycomb structure (Meaburn, Wang, & Bryce 1995), which led to the proposal by Redman et al. (1999) of the model in Figure 9. Here, a supernova blast wave encounters fragments in the nearside of its host giant shell and creates approaching ablated flows in the perimeters of the honeycomb cells as observed. The honeycomb structure only becomes apparent in Fig. 8 if the sightline is closely parallel to the flows.

4.2. *The M 42 Proplyd Monopolar Jets*

More speculatively, Meaburn, Graham, & Redman (2003) have suggested that the monopolar microjets (Meaburn et al. 1993; Bally, O'Dell, & McCaughrean 2000) from the "proplyds" in the core of M 42 could be the consequence of the ejection of ablating bullets from the central YSOs of the proplyds rather than collimated outflows as in Henney et al.

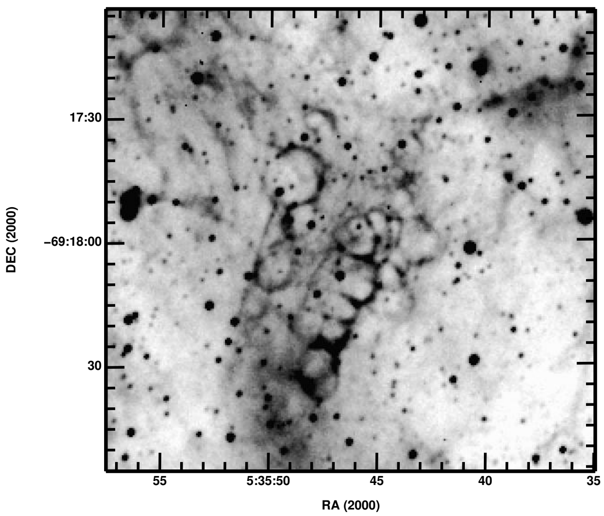

Fig. 8. An image of the Honeycomb nebula in the halo of 30 Doradus.

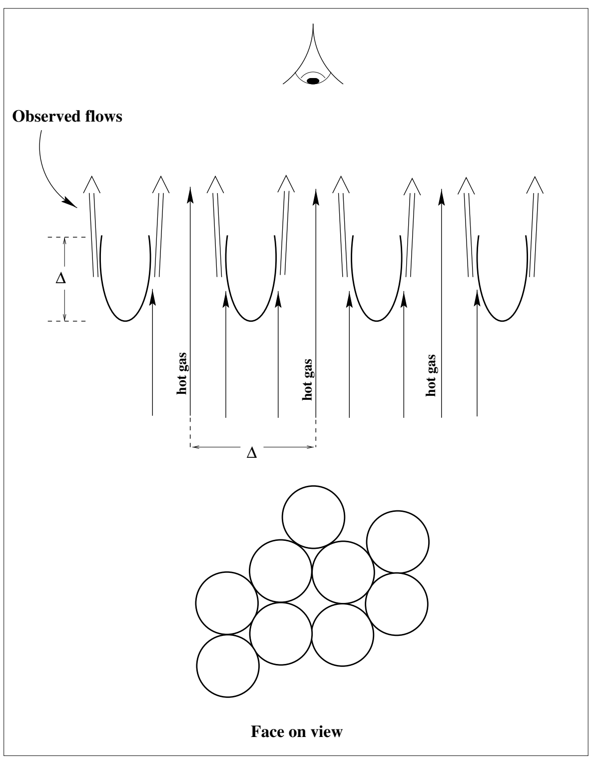

Fig. 9. A sketch of a model of the Honeycomb nebula. The morphology is generated as a supernova blast wave breaks through the weak points of an unstable old giant shell. The weak points are separated by approximately the thickness of the old shell.

(2002). However, the observational evidence is not conclusive for such an interpretation but it seems worth considering in view of the many bullet-like phenomena found in diverse circumstellar environments.

5. CONCLUSIONS

The evidence for ablated flows has been presented for a variety of sources investigated in our observing programmes. This includes planetary nebulae, the ejecta of LBV stars, H II regions and supernova remnants. Even if some doubts exist in particular cases considered here it is clear that the physics of mass-loaded flows developed by John Dyson and his collaborators is crucial to the understanding of a wide range of circumstellar and interstellar phenomena.

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John Meaburn and the banner (Photo: Alan Pedlar).

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