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# IONIZATION FRONT INSTABILITIES

R. J. R. Williams

Department of Physics and Astronomy, Cardiff University, UK

## RESUMEN

Las nebulosas fotoionizadas resueltas, tales como las regiones H II y las nebulosas planetarias, tienen estructuras complejas y dinámicas pero el origen y la evolución de estas estructuras permanecan como temas controvertidos: ¿se deben a las inhomogeneidades en el gas ambiental, o a una inestabilidad intrínsica del choque y del frente de ionización que rodean la región? Describo trabajos numéricos y analíticos que investigan la estabilidad de estos frentes de ionización en un intento de ayudar a resolver estas preguntas.

## ABSTRACT

Resolved photoionized nebulae, such as H II regions and planetary nebulae, have complex and dynamic structures, but the origin and evolution of these structures remain controversial: is it the result of inhomogeneity in the upstream gas, or intrinsic instability of the shock and ionization front surrounding the region? I describe numerical and analytic work which investigates the stability of ionization fronts, aiming to help resolve these questions.

*Key Words:* **H II REGIONS — ISM: KINEMATICS AND DYNAMICS — PLANETARY NEBULAE**

## 1. INTRODUCTION

Many of the most spectacular of astronomical objects result from emission from photoionized gas. Examples include H II regions, in which the intense ultraviolet radiation emitted by young, massive stars photoevaporates the molecular material from which the stars originally formed, and planetary nebulae, where a lower mass star, coming to the end of its life as a white dwarf, is hot enough to ionize the material blown off in its final stages of evolution.

The sizes of H II regions vary from sub-parsec to galactic scales. I will concentrate here on the properties of classical H II regions, which surround one or a few massive stars and which have escaped their enveloping molecular material to be observable in optical recombination lines. Well-resolved examples such as the Eagle nebula (M 16) and Orion (M 42) nebula have intricate structures on a variety of scales, ranging from small-scale wisps and globules to large columns of neutral gas. Spectroscopy confirms this impression of dynamic activity, with line widths of up to $30\,\mathrm{km\,s^{-1}}$ observed in the ionized gas (Castañeda 1988; O'Dell 2000), and significant velocities observed in the neutral gas which surrounds it. Planetary nebulae grow as they get older, but their dynamics will often be dominated by the effects of the fast wind blowing from the central star. I will discuss one example, the Helix nebula, in which the wind is believed to be weak and the dynamics may be dominated by photoevaporation.

The simplest models of the structures of H II regions, which assume spherical symmetry, predict that for most of their life the ionized gas should be relatively uniform and quiescent. The origin of the structures that are observed has long been controversial. Do they result from intrinsic instabilities of the ionization front (IF) or overall H II region structure (as suggested by Frieman 1954 and Spitzer 1954), or do they simply reflect the clumpy structure of the molecular gas advected into the regions (Kahn 1958; Pottasch 1958)?

In this paper, I will describe work modeling the stability of IF, and the structure of individual elements of photoionized nebulae. The IF will often be preceded into the neutral gas by a pressure wave or shock, so that an important parameter is the ratio of the radius of the nebula to the thickness of the swept-up layer between the discontinuities. The differences between the flows with thick or thin swept-up layers were emphasised in a global context by García-Segura & Franco (1996). Whether, as assumed by these authors, this thickness is determined by the efficiency of cooling in the swept-up gas, or whether the upstream shock is weak, as in an H II region that is old or has an open geometry (a blister or "champagne flow"), both limits are of practical importance. I will first discuss the stability of fronts where the upstream neutral gas is at rest (that is, the extreme case of a thick shell), and then where a thin dense shell of gas exists between IF and shock.

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## 2. THE STABILITY OF PLANE IONIZATION FRONTS

IF are classified as R-type or D-type, depending on the speed at which gas passes through them. Gas is advected into a weak R-type front at supersonic velocity, and exhausts at a marginally lower, but still supersonic, velocity. In contrast, a D-type front accelerates neutral gas from subsonic flow closer to the sound speed (which is also substantially greater in the ionized gas) when it is a weak front, or beyond the sound speed for a strong front. While R-type fronts have interesting stability properties (Newman & Axford 1967; Williams 1999), I will concentrate on the more observationally significant D-type IF.

The linear stability of IF may be analyzed in a similar manner to the the Rayleigh-Taylor instability. Treating the structure of the flow in the ionized and neutral components separately, equations can be derived relating the surface perturbations in the position, velocity, and pressure for evanescent solutions. Matching the surface perturbations between the components gives a dispersion relation for interface waves. The case of ionization fronts differs from the Rayleigh-Taylor instability in that there is a finite mass flux through the interface between the phases (and that there need be no net acceleration of the interface to trigger instability).

Vandervoort (1962) analyzed the stability of weak D-type IF assuming that there was no recombination in the ionized gas, i.e., that the radiation flux incident on the interface was independent of the ionized gas flow. In this case the fronts were unstable in general, whether the ionizing field was incident at right angles to the interface between ionized and neutral gas, or raked to it. For the case of normal incidence, this can be understood qualitatively by considering the flow through a surface wave. The divergence of the flow streamlines at the apex of the perturbation (closer to the radiation source) means that, for a fixed flux, the pressure is lower than where the flow streamlines are converging close to the furthest part of the instability. The result of this pressure in the neutral gas is to divert flow towards the apex, further amplifying the instability.

However, Kahn (1958) had already pointed out the likely role of recombination in saturating such instabilities. The additional path-length of ionized gas in the troughs of the instability will tend to decrease the flux through its surface. Axford (1964) applied this reasoning to Vandervoort's analysis for the case of perpendicular irradiation, by including the result of the decrease of radiation flux due to recombination in the jump conditions applied to the ionized/neutral

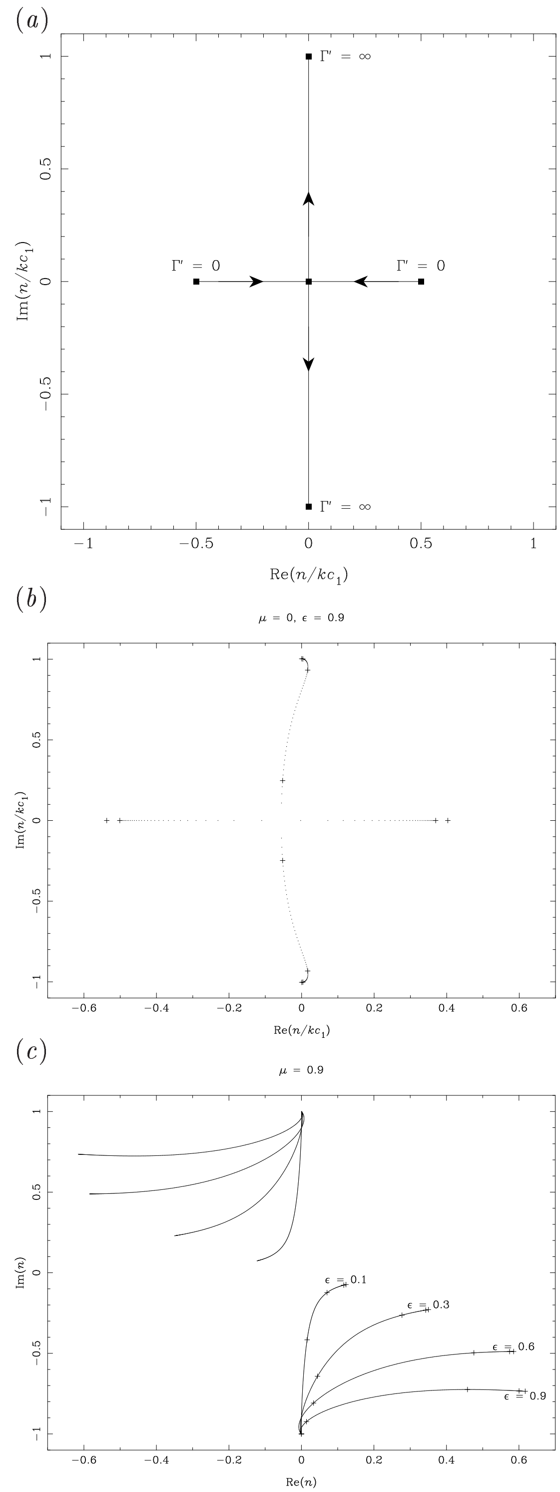


Fig. 1. Dispersion relations for surface modes (Williams 2002). ($a$) Normal incidence with $c_2/c_1 \rightarrow \infty$; ($b$) Normal incidence, $c_2/c_1 = 0.1$, exhaust Mach number $\varepsilon = 0.9$; ($c$) Inclined incidence with $\tan\theta = 0.6$, for a range of exhaust Mach numbers, $\varepsilon = v_2/c_2$.

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boundary. Axford confirmed that the instability was quenched by recombination, although he found that the effects of density perturbations in the ionized gas were rather greater than the simple recombination-distance effect. In essence, an interference pattern of over- and under-densities appears in the ionized flow from the surface of an IF perturbed by a periodic wave form, and it is only when the radiation field is integrated through this waveform that the total effect on the instability can be evaluated.

Axford's (1964) results are shown in Figure 1*a*. These results were obtained for the simpler case in which the ratio $c_2/c_1$ of the sound speeds of the ionized and neutral gas, tends to infinity. The growth rate of the unstable modes decreases as their wavelength approaches the recombination length, $c_2/n_2\alpha_{\rm B}$. However, the short wavelength modes remain unstable (although it was argued that the finite width of the IF might saturate the instability here), and even in the long-wavelength limit, the modes are only ever marginally stable in this approximation.

More recently, Sysoev (1997), Ryutov et al. (2001) and the present author (Williams 2002) have revisited the stability problem. For normal incidence, Axford (1964) found that for long wavelengths the roots of the dispersion relation were marginally stable: to be certain about stability, processes neglected in his analysis have to be included. Ryutov et al. (2001) treated the stability of inclined fronts in general, by assuming that the pressure at the IF was related uniquely to the incident ionizing flux. By treating the dispersion relation (including the explicit solution for the perturbations in the ionized gas) for finite $c_2/c_1$, Sysoev (1997) found that while the flow was genuinely stable for intermediate wavelengths, it became unstable again at long wavelengths (see Figure 1*b*). This may be understood as a result of the finite time the ionized flow takes to develop the structure corresponding to the present surface form of the IF: the lag present in this system allows an overstability to develop. Williams (2002) confirmed Sysoev's (1997) results for normal incidence, and discovered that even when recombination is included and the "ablation pressure" determined explicitly, *inclined* IF are unstable at essentially all wavelengths.

Figure 2 shows the results of numerical simulations of the development of an IF instability, calculated using an adaptive mesh refinement code (Williams 2002). A small initial flow perturbation grows first to form fine-scale crenellations of the IF structure. This demonstrates the presence of the small-scale instability for these flows, but also shows that it saturates when its amplitude is comparable to the recombination length (compared to the wavelength criterion found by Axford 1964).

When modeled in finer detail, the saturated spikes have a characteristic structure, with plateaus in the IF surface separated by narrow spikes of ionized gas reaching into the neutral region. The individual fingers jostle and interact, merging when they are forced too close, and breaking apart when allowed to broaden. Downstream in the ionized gas in plane-parallel simulations, there is very little structure in the density of the flow, but significant changes in velocity, which are only gradually damped by the weak numerical viscosity. In the context of a flow from the surface of a dense globule or column of neutral gas, this velocity structure would lead to differences in the density as the flow expanded, and hence to observable striations roughly perpendicular to the IF surface.

Eventually, however, long-wavelength instabilities begin to grow. Figure 2*b* shows the clear separation in wavelength between the saturated small-scale instabilities and those growing on the larger scale. The wavelength and growth-rate of these large-scale instabilities are an excellent match to those found from the linear analysis, confirming that it is reasonable to treat the smooth flow in this manner even when non-linear small-scale structure is present. Eventually, the long-wavelength instabilities grow to non-linear amplitude, forming large columns of neutral gas directed into the ionized region. While these columns are strikingly reminiscent of the structures observed in M 16 and other H II regions, it is as well to be cautious in interpreting them as such columns can form for a multiplicity of reasons (Williams, Ward-Thompson, & Whitworth 2001).

As the instabilities grow, the mean position of the IF moves away from the source of the ionization. This implies that the conditions in the flow, when looked at on the largest scales, have become closer to D-criticality, the case where subsonic flow of neutral gas into the IF leads to sonic flow of ionized gas in its exhaust. Hence even in closed geometries, effectively D-critical fronts may be more common than suggested by one-dimensional analysis. It remains, however, to model in detail the effects of diffuse radiation, dust absorption, radiation pressure and net acceleration on these instabilities.

## 3. SWEPT-UP SHELLS

The treatments in the previous section all focussed on the case in which the neutral gas ahead of the shock is uniform, at least on the scale of the

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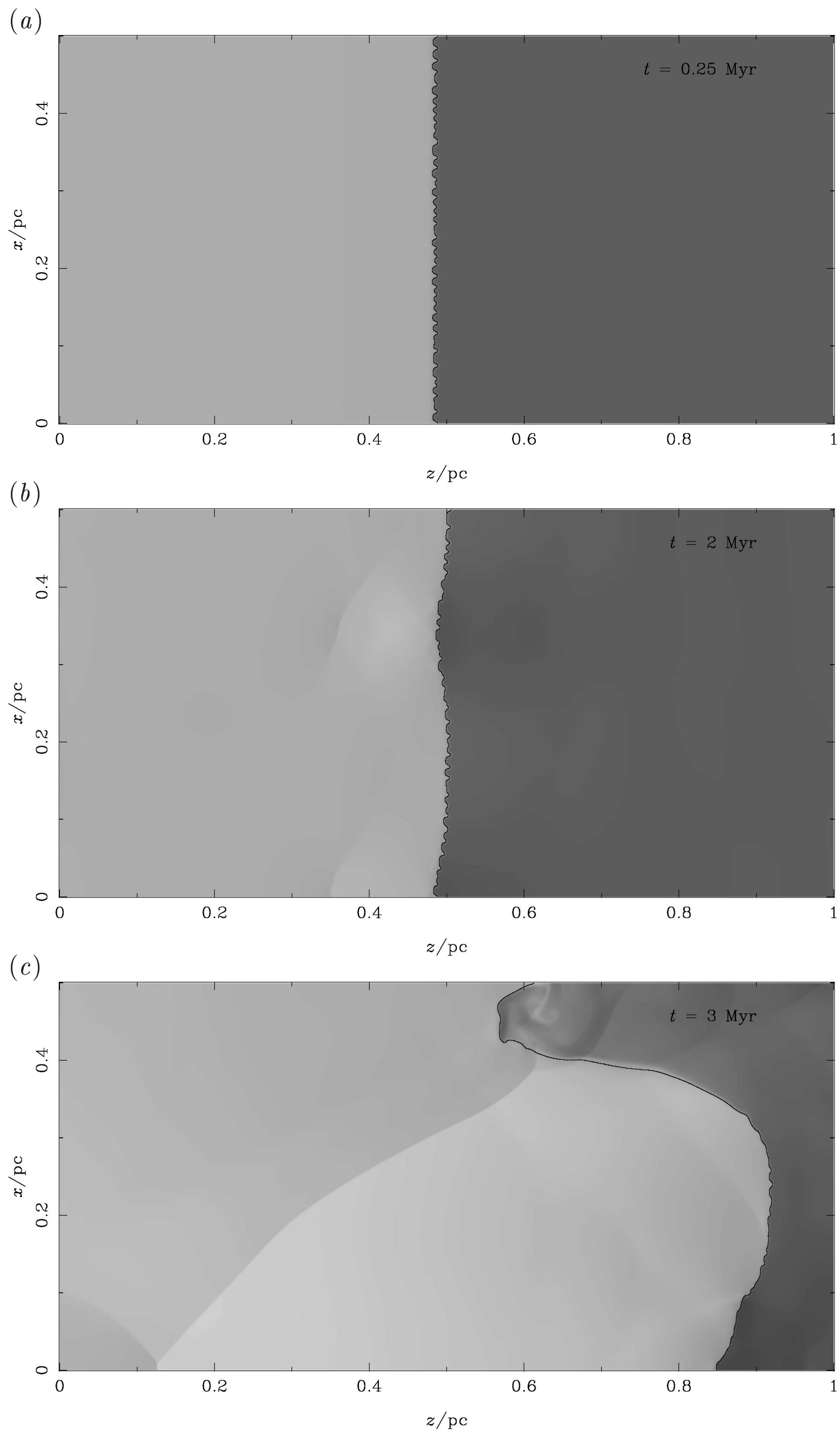


Fig. 2. Development of instability for an IF with exhaust Mach number 0.9. (*a*) The fine-scale instability grows rapidly, but saturates at an amplitude comparable to the recombination length. Longer-wavelength instabilities eventually appear (*b*), and grow to form columnar structures (*c*).

perturbations. However, the overpressured ionized gas will generally drive a shock into the surrounding neutral medium. When the layer of material swept up by the shell but yet to be photoionized is thin, soon after the shock has been launched, in closed geometries and particularly when the upstream neutral gas can cool effectively, the system of shock and IF has to be analyzed as a whole.

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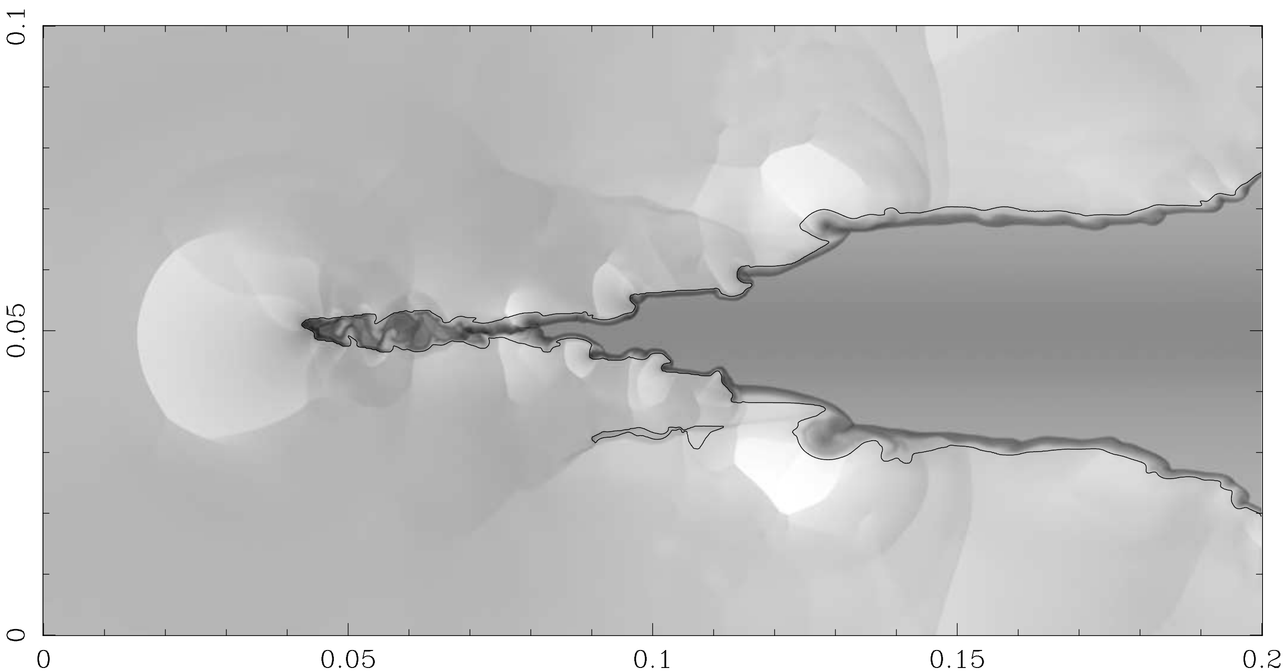


Fig. 3. Propagation of an IF into a region with a weak density gradient. The ionizing radiation is incident from the left, and the upstream neutral density is smoothly varying, with an overdensity by a factor 10 in the midplane. This image shows thin-shell instabilities in the main IF, and the injection of neutral material into the ionized region in the mid-plane.

The stability of thin layers bounded by IF and shocks was analyzed by Giuliani (1979). The combined system shows typical thin-shell instability modes (Vishniac 1983). García-Segura & Franco (1996) describe the development of the instability in an ionized nebula: where the IF and shock are most advanced, they drive the neutral material which they sweep up apart, directing it into the slowest moving parts of the combined front. The resulting changes in column density across the shell allow the advanced regions to accelerate yet further.

This process tends to accentuate the curvature of concave regions of the shell, until eventually a gradient discontinuity appears. The structure resulting from this breakdown of the smooth profile of the IF and shock bounded shell is analogous to that of a shaped charge (Batchelor 1967). Cantó, Tenorio-Tagle, & Rózyczka (1988) discuss the case where two parts of such a dense shell collide at an angle leading to the formation of a jet from the apex. Recent experimental studies in laser-driven cavities and magnetic $z$-pinches have confirmed the effectiveness of this mechanism for driving directed flows (Farley et al. 1999; Lebedev et al. 2002). For a thin-shell implosion (Kimura & Tosa 1991), material escapes in streams behind the interaction regions, while the pressure of gas in these regions may be very high.

The structure of the global flow is critically dependent on the properties of the doubly-shocked gas while it resides in the interaction regions. For gas with a stiff equation of state, the interaction can lead to the formation of both a reservoir of material at the resolved velocity of the collision and a jet with a small amount of rapidly moving material directed upstream. That gas might be expected to escape in both directions from such an interaction is apparent by comparison to the structure of internal working surfaces in jets (Falle & Raga 1993), where the antiparallel inflows of material drive gas to escape from all sides. In the present case, the jet of rapidly moving material would be driven forward into the neutral envelope. This was the effect for which shaped charges were designed (Batchelor 1967), but structures such as the ring of bullets around the waist of $\eta$ Carinae may also be examples of this process—certainly, the linear relation between proper motion and distance throughout this nebula *suggests* that the dynamical origin of the motions was close in time to the original explosion.

This picture of thin-shell instability may also be relevant to the structure of the Helix nebula (Williams, Henney, & Steffen 2003). The Helix is an old planetary nebula in which the wind of the central star is weak, so its structure is likely to be

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dominated by the dynamical effects of ionization. In the standard picture of the structure of bipolar PNe, the expansion of the bubble in the equatorial plane is held back by larger densities in the upstream material. Figure 3 is the result of a numerical calculation that illustrates the development of an IF driving a thin shell into such a density structure. Small thin-shell instabilities develop across the surface of the IF, but the dominant structure is in the equatorial plane, where the passage of the main IF/shock leaves behind dense globules of neutral gas.

This calculation is performed in slab symmetry, so the structure that results in three dimensions is a matter for conjecture. However, there are some features of the Helix nebula that seem to suggest that globules such as those observed may be the result.

As the gas passes through the shock leading the IF, it is subject to an increase in pressure. If the knots were features present upstream, they would be expected to decrease in radius. However, as there are $\simeq$ 3500 clumps with radius $2 \times 10^{15}$ cm distributed in a thick disk at a distance $3 \times 10^{17}$ cm from the central star, the volume filling factor of the clumps is $(\Omega/4\pi)^{-1}10^{-3}$, while they cover about $(\Omega/4\pi)^{-1}4 \times 10^{-2}$ of the sky as seen from the white dwarf (where $\Omega$ is the solid angle subtended by the thick disk, $\Omega/4\pi \simeq 0.1$). The combined winds of the globules, treated as a cylindrical flow, are sufficient to blow a toroidal bubble in the nebula similar in size to the region of low H$\beta$ surface brightness in the region filled by the knots, in a similar fashion to the low-density region seen at the head of the left-most globule in Fig. 3.

So most of the sky as seen from the white dwarf is presently covered by knots, and if they have collapsed by a factor of 100, they would have initially filled almost the entire volume of the thick disk! (However, the escape of material along the poles of the nebula will prevent the actual compression being this great.)

However, this calculation neglects the mass of neutral hydrogen in the tails behind the observed knots. The ionized gas at the surface of the knots has a density of $\sim 10^3\,\mathrm{cm}^{-3}$, while that of the molecular gas in the heads is $\sim 10^6\,\mathrm{cm}^{-3}$. The tails are surrounded by gas with density $\sim 10^2\,\mathrm{cm}^{-3}$, so if their molecular density is larger by a similar factor to that found in the heads, most of the neutral gas in the inner region of the Helix may in fact be in the tails. Just as in M 16, the distinctive head region may simply be the reaction of the tail to direct illumination, rather than the tail having formed in the shadow of a globule. The covering factor of tails to the observer is of order unity, and their surface density on the basis of the previous estimate, $\sim 4 \times 10^{20}\,\mathrm{cm}^{-2}$, is similar to the surface density, $\sim 1.2 \times 10^{20}\,\mathrm{cm}^{-2}$, of $1\,M_\odot$ of material swept up by the main IF at 0.3 pc from the star, as might be expected if they resulted from matter which had escaped inwards from such a shell and been subject to non-axisymmetric instabilities.

In conclusion, photoionized flows have fascinating and dynamic observed structures, and fascinating dynamics. Much work remains to determine whether a causal link exists between these statements.

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R. J. R. Williams: Department of Physics and Astronomy, Cardiff University, PO Box 913, Cardiff CF24 3YB, UK (robin.williams@astro.cf.ac.uk).