

Optical kinematics in the Cygnus Loop

II. Interpretation

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Abstract. We describe and analyze the results of imaging Fabry-Perot observations in the lines of H α and [O III] λ 5007 Å made of selected regions in the Cygnus Loop supernova remnant. The measurements themselves, which are presented in a companion paper (Greidanus & Strom 1991), concentrated on filaments in the north-central area (the “carrot”, NGC 6974), but also included a field along the northeastern edge (NGC 6992). After briefly recapitulating the results in a qualitative sense, we consider how the gas kinematics can best be interpreted. The cloud model provides a natural explanation for the general lack of correlation between the H α and the [O III] emission, since the two will radiate at times significantly different on gas-dynamical time scales. However, we find little evidence for the velocity splitting in [O III] expected from shocks moving into a cloud from opposite sides. The sheet model, in which a radiative blast wave is viewed as a deformed sheet, and “filaments” are intensity enhancements caused by foreshortening when the sheet runs roughly tangentially to the line of sight, is generally consistent with the pattern seen in [O III]. In particular, the bright filaments in [O III] consistently appear at low radial velocities, while the diffuse emission spans a larger range. The H α emission, however, can only be explained by invoking additional kinematical elements.

We argue that a ubiquitous, narrow [O III] component is associated with the remnant, and probably results from photo-ionized gas in the precursor region. It may also be present in H α , but would be masked by geocoronal emission. The existence of this component enables us to estimate the systemic velocity of the Cygnus Loop ($8 \pm 3 \text{ km s}^{-1}$ LSR), and derive a kinematic distance of $1.3 \pm 0.7 \text{ kpc}$.

Key words: supernova remnants: Cygnus Loop – radial velocities – lines: profile – shock waves – interstellar medium: kinematics and dynamics of

1. Introduction

This paper discusses observations of the small-scale radial velocity structure of optical filaments in the Cygnus Loop. These

observations were done in the emission lines of H α and [O III] λ 5007 Å, and have been published as Paper I (Greidanus & Strom 1991).

The Cygnus Loop is the prototype of an evolved supernova remnant. Its bright optical emission consists of a number of complex filamentary nebulosities, arranged in a shell three degrees in diameter. On the scale of the remnant, there is a good general correlation between emission from the various wavelength regimes: radio (Keen et al. 1973), infrared (Braun & Strom 1986), optical (cf. Palomar Observatory Sky Survey) and X-ray emission (Ku et al. 1984) all follow the roughly circular shell with an irregular breakout in the south. The Cygnus Loop is thought to be the result of a supernova blast wave running outwards through the surrounding medium; it is evolved in the sense that supernova ejecta are not seen in the shell anymore, only the interstellar matter that has been swept up. At an estimated distance of 770 pc (Minkowski 1958), its relative proximity makes it possible to study the object in great physical detail, 1'' equalling 10^{16} cm . In the classical picture (Bychkov & Pikel'ner 1975; McKee & Cowie 1975), the X-rays originate in gas heated to coronal temperatures by the 400 km s^{-1} adiabatic blast wave moving through a 0.2 cm^{-3} density intercloud medium, while the optical emission is from radiative $\sim 100 \text{ km s}^{-1}$ shocks driven into $\sim 5 \text{ cm}^{-3}$ density clouds embedded therein. Furthermore, the infrared emission is from dust grains heated in the coronal gas, and the radio is synchrotron radiation produced by a combination of the interaction of a compressed relativistic plasma with magnetic fields (Duin & van der Laan 1975) and particles accelerated by the shock front.

The radiative shocks produce an optical spectrum of Balmer lines and forbidden metal lines, notably of [S II], [N II], [O I], [O II] and [O III] (Miller 1974; Fesen et al. 1982; Hester et al. 1983), and a corresponding UV spectrum (Raymond et al. 1980; Benvenuti et al. 1980). These spectra compare relatively well with steady radiative-shock models (Raymond 1979; Shull & McKee 1979), with shock velocities of 70–130 km s^{-1} deduced; the shock models have a large number of parameters however (pre-shock density, magnetic field, abundances, ionization), and some important discrepancies remain, mainly in the high observed [O III]/H β ratio. These have been explained by a combination of different shock velocities, and – more successfully – by incomplete recombination of the post-shock cooling zone (Raymond et al. 1980). The latter effect, in combination with the embedded clouds picture with sufficiently small clouds, may also explain the

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differences in morphology between emission from lines of different ionization states.

In addition to the emission from the radiative shocks, faint Balmer (and very faint forbidden line) emission has also been observed from an adiabatic shock at the most extreme edge of the remnant (Raymond et al. 1983; Fesen & Itoh 1985), which is estimated to move at 200 km s^{-1} through a 1 cm^{-3} density medium. The shock velocity deduced depends on the electron-ion temperature equilibration mechanism. Deep images show that this emission bounds the X-ray emission externally (Hester et al. 1986).

An alternative to the small-cloud model has been put forward by Hester & Cox (1986) and Hester (1987) (and somewhat differently by Falle & Garlick 1982), who argue that the blast wave is radiative over a large part of the remnant through its interaction with a large cloud, and that the X-ray emitting gas is fully contained within the optical shell. In this view, the filaments are places where the radiative shell, which suffers from large- and small-scale distortions, is seen near tangency. This model is supported by morphological and kinematical evidence, by observations that the filaments must be deep, and from the lack of spectral change between filaments and diffuse emission (Miller 1974; Hester et al. 1983; Raymond et al. 1988). The model contrasts with the notion of rope-like filaments, as might be formed in the presence of a magnetic field, that have been used to explain radio observations (e.g. Straka et al. 1986). In yet another interpretation (Boulares & Cox 1988) cosmic rays dominate the remnant.

Early large-scale kinematical studies of the Cygnus Loop were done in $\text{H}\alpha$ by Minkowski (1958), who finds radial velocities (LSR) between -100 and 70 km s^{-1} in 25 positions. He fits the data with a thick shell, expanding at 116 km s^{-1} ; combined with a proper motion of $0.03'' \text{ yr}^{-1}$ (Hubble 1937) this gives the distance of 770 pc. He finds no systematic differences between the radial velocities of filaments and diffuse features. Doroshenko (1970) studied the kinematics with Fabry-Perot observations; she finds LSR velocities between -15 and 110 km s^{-1} and fits them with the same large-scale expansion. Although filaments and diffuse emission are not distinguishable in radial velocity, for the distribution of profile widths she finds, however, a mean and standard deviation of $40 \pm 15 \text{ km s}^{-1}$ in the filaments and $63 \pm 22 \text{ km s}^{-1}$ in the diffuse features. Doroshenko & Lozinskaya (1977) detect weak high-velocity $\text{H}\alpha$ from between the filaments at velocities between $\pm 170 \text{ km s}^{-1}$ in the form of an underlying plateau in the line profile at $\sim 5\%$ of the level of the bright, narrower emission. Even higher radial velocities are found by Kirshner & Taylor (1976), -270 – 200 km s^{-1} ; they are attributed to the Balmer emission from the fast non-radiative shock.

The detailed kinematics of the Cygnus Loop have been investigated by Shull et al. (1982) using long-slit echelle spectra in $\text{H}\alpha$, $[\text{N II}]$ and $[\text{O III}]$. They find that the profiles of filaments can be fit with one to three Gaussian components, separated by 10 – 30 km s^{-1} , having widths in the range 30 – 60 km s^{-1} . Where diffuse emission is observed it has a width of $\sim 140 \text{ km s}^{-1}$. This non-thermal broadening is interpreted as micro-turbulence within the filaments.

2. Summary of the observations

In Paper I, the morphology and kinematics of each of the six, 6'-sized fields observed in the Cygnus Loop have been described.

The observations were analyzed at a resolution of $6''$ spatially, and 27 and 20 km s^{-1} in velocity for $\text{H}\alpha$ and $[\text{O III}]$, respectively. Here, a summary of the results will be given.

As far as the morphology of the line emission is concerned, many of the characteristics that have been found in previous studies are confirmed (Fesen et al. 1982; Hester et al. 1983). In almost all fields the detailed correspondence between $\text{H}\alpha$ and $[\text{O III}]$ brightness distributions is not very good, the discrepancy increasing with resolution. On a large scale the same patterns are visible, but $[\text{O III}]$ has more individual filaments, that have a higher contrast with respect to their surrounding smooth, low-level emission, while the $\text{H}\alpha$ filaments are less sharp and the diffuse emission surrounding them is more clumpy. Especially at the original $2''$ resolution (Paper I, Sect. 3.1), most $[\text{O III}]$ filaments do not have $\text{H}\alpha$ counterparts and vice versa, but a few do, in which case they may overlap in places but move apart by up to typically $\sim 5''$ elsewhere on the same filament. The $\text{H}\alpha$ emission without $[\text{O III}]$ counterparts is broad and patchy, perhaps not really deserving to be called filamentary. Profile maximum maps (parameter a defined in Paper I, Sect. 2.2) show especially the weak filaments with somewhat more contrast than the profile integral maps (parameter I_i), since they have less contribution from the broad background component; they are noisier however.

That the provisional intensity calibration (Paper I, Sect. 3.2) is correct at least to an order of magnitude may be confirmed by comparing the present values to previously published results (e.g. Fesen et al. 1982). The maximum intensity in the filaments is 140 – 380 (-600) in $\text{H}\alpha$ and 100 – 300 (-700) in $[\text{O III}]$, in units of $10^{-6} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$, corrected for $E(B-V)=0.08^m$ (Paper I, Sect. 3.2), and in a $6''$ beam; the bracketed high values occur in field E1. Typical intensities in the diffuse emission are ~ 40 ($\text{H}\alpha$) and ~ 30 ($[\text{O III}]$).

The classification of the emission into the four components discussed under field C2 (Paper I, Sect. 4.1: filamentary, diffuse, broad background and narrow $[\text{O III}]$) seems applicable in most fields. An overview of the component velocities is given in Table 1. These velocity ranges do not include the most extreme values but rather the main extent. The broad $\text{H}\alpha$ background component is centered in all fields around 65 km s^{-1} , except C6 and E1, where it is not detected, and has a width of $\sim 120 \text{ km s}^{-1}$. The central velocity of the broad $[\text{O III}]$ component is not exactly the same in all fields, as shown in the table. Its width is $\sim 100 \text{ km s}^{-1}$ in all cases; it is not detected in field C6 and not clear in fields C5 and E1. The very low level of this component makes these values not very well determined. The narrow $[\text{O III}]$ component is only seen in C2 and C4.

A different way of looking at the data is by scatter diagrams, which plot the values of two parameters against one another for all pixels in a region. Figure 1 plots the location v_a of the profile maximum against its value a , i.e. velocity against intensity, for fields C2, C3, C6 and E1. All fields have their strongest emission (that occurs in the filaments or in the strongest filament) at a relatively low velocity, at a comparable value for $\text{H}\alpha$ and $[\text{O III}]$, but different from field to field; the maximum brightness also has a large spread from field to field however. Weaker emission (occurring in weaker filaments and in diffuse emission) is found within an ever broader velocity range, with a preference for positive velocities. The choice of these parameters instead of profile median v_m versus profile integral I_i makes the pattern in the scatter diagrams somewhat more prominent, but also noisier.

Table 1. Overview of typical radial velocities (profile medians) occurring for the various emission components. The last column gives the median overall velocity difference. All values in km s^{-1} (LSR)

Field	H α		[O III]				[O III] – H α Difference
	Filaments	Diffuse	Filaments	Diffuse	Broad	Narrow	
C2	30–50	40–130	20–90	60–150	90	5 ± 2	6 ± 25
C3	20–40	30–70	10–60	20–100	50	—	3 ± 20
C4	30–50	40–100	0–80	40 ^a –110	60	10 ± 3	5 ± 20
C5	20–40	20–60	–10–80	20 ^b –180	(40)	—	-5 ± 15
C6	20	20	10–20	10–40	—	—	5 ± 10
E1	–5–20	–20–40	–15–40	–40–80	(35)	—	0 ± 15

^a Negative component to –40.

^b Negative component to –20.

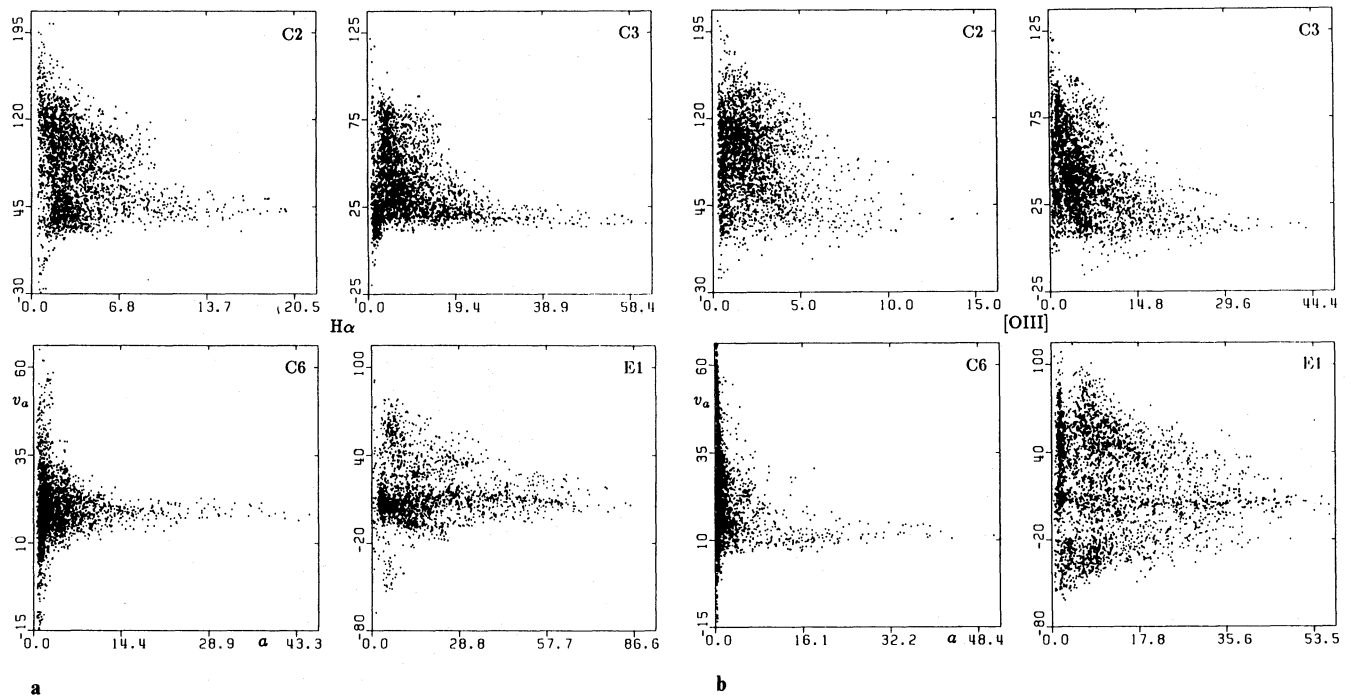


Fig. 1a and b. Scatter diagrams of velocity (vertical axis, profile mode v_a , km s^{-1} LSR) against intensity (horizontal axis, profile maximum α , $10^{-5} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$), for fields C2, C3, C6 and E1. **a** In H α ; **b** in [O III]. Note the different scales

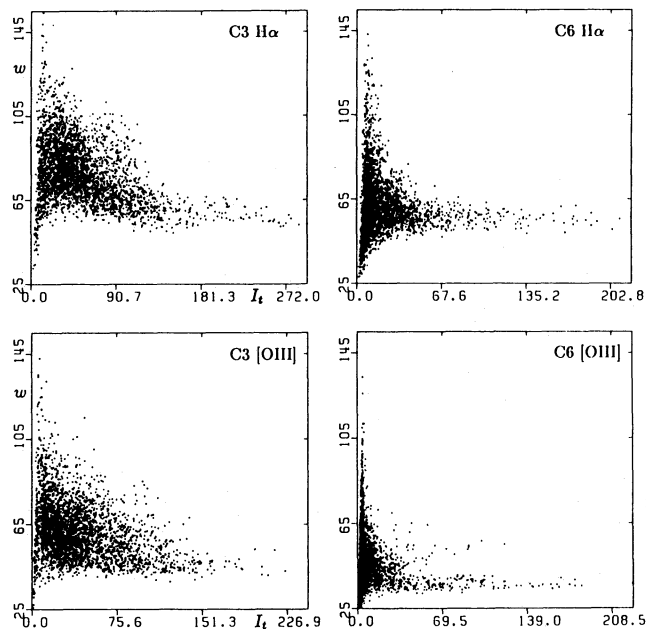
(The velocity fields of Paper I presented profile median, and were consequently less noisy and somewhat more biased to central velocities by the presence of the broad background component.) The cutoff of 3σ (Paper I, Sect. 2.2) that was used will produce a spurious detection at a random velocity with a frequency of 4% per profile, considering typical numbers of 12 independent points per profile integration region and a level of 10 photon counts per beam. The velocity extent at low intensities is however influenced by the presence of the broad background component, which lifts up the profile values over the detection limit. For profiles with more components, only the strongest one is plotted in these scatter diagrams; as a consequence, the components at negative velocity, which are generally weaker, are under-represented if present. The character of the scatter diagram of field C3 is similar

to that of fields C4 and C5, which are not included. Field C2 has an indication of being bimodal with a secondary concentration around 90 km s^{-1} , while field C6 has only little emission at outlying velocities (note the expanded velocity scale). The diagram of field E1 shows a markedly different character, most notable in [O III], with components at positive, zero and negative velocities separated.

Profile widths are mainly governed by profile complexity and the presence of the broad component; there is no clear distinction between filaments and diffuse emission. An overview of typical values is given in Table 2; the actual values are broadly distributed around these. Unresolved loci of very large widths ($\sim 120 \text{ km s}^{-1}$) follow the edges of [O III] filaments in many cases; this effect is seen even more clearly in profile skewness. The

Table 2. Overview of typical profile widths (FWHM, km s^{-1}) occurring in the various fields

Field	$\text{H}\alpha$		$[\text{O III}]$	
	Filaments	Diffuse	Filaments	Diffuse
C2	60	90	30–70	30–70
C3	50	$\lesssim 100$	35	65
C4	65	100	40–100	40–100
C5	70–110	70–110	40–90	40–90
C6	50	50	30	40–50
E1	60	110	40	40–85

**Fig. 2.** Scatter diagrams of profile width (vertical axis, w , km s^{-1}) against profile integral (horizontal axis, I_t , $10^{-6} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$), for fields C3 and C6 in $\text{H}\alpha$ and $[\text{O III}]$

overall distribution of profile widths is not bimodal, and has a median and RMS dispersion of $73 \pm 16 \text{ km s}^{-1}$ in $\text{H}\alpha$ and $45 \pm 19 \text{ km s}^{-1}$ in $[\text{O III}]$ in all fields, except in field C6 that has 50 ± 16 ($\text{H}\alpha$) and 35 ± 12 ($[\text{O III}]$), in $\text{H}\alpha$ field C2 (73 ± 28), and in $[\text{O III}]$ field E1 (60 ± 24). These numbers have been corrected for the occurrence of multiple profiles that have been significantly detected.

Scatter diagrams of profile width against intensity (Fig. 2) show that the narrowest profiles occur on the brightest emission with a trend to broader ones on weaker emission. (These widths are not corrected for instrumental broadening.) Most other fields have diagrams similar to that of field C3. Field C6 has the narrowest profiles; the high intensities cluster around 55 km s^{-1} in $\text{H}\alpha$ and around 35 km s^{-1} in $[\text{O III}]$, about a factor of two over the estimated resolution (also see remarks about width in Paper I, Sect. 4).

In kinematics as well as morphology the $\text{H}\alpha$ and $[\text{O III}]$ emission are quite distinct. The crisper character of the $[\text{O III}]$ is also maintained when the emission distribution is viewed in a data cube. In most cases the filamentary/diffuse component of $[\text{O III}]$ is concentrated in a thin surface which in numerous instances is shaped in such a way as to curve outward to high velocities where the brightness is lowest while being pinched toward zero velocity on the filaments. In other places deviations from this pattern occur, with no or only small deformations of the emission surface at the locations of filaments. Sometimes a similar surface is present at the negative velocity side which mirrors the positive one in character (not in detail); in this case the surfaces may bend around to connect, or join at the locations of filaments. In other cases, however, the $[\text{O III}]$ emission is distributed in a more complicated, seemingly random, clumpy way. The field on the edge, E1, has many similarities to the other fields; it is different in the sense that it is brighter, it shows double profiles in $[\text{O III}]$ over a much larger area, and the diffuse emission does not curve to zero velocity on the locations of filaments as clearly as in the other fields.

The $\text{H}\alpha$ emission does not have as much kinematic structure as the $[\text{O III}]$. In most fields its velocity changes little, irrespective of brightness. Frequently, there are regions where the emission has a cloudy distribution in the data cube. Channel maps near 0 km s^{-1} often show a more filamentary structure than the total intensity distribution, but the effect is much less than in $[\text{O III}]$. In Fig. 3, the $\text{H}\alpha$ and $[\text{O III}]$ kinematics are compared in scatter diagrams. Most fields have one subset of points where the $\text{H}\alpha$ and $[\text{O III}]$ velocities correlate, and one subset where the $\text{H}\alpha$ velocities are constant while $[\text{O III}]$ velocities vary. The correlating subset can in all cases be fitted by a line with slope 1 and offset 0.

As a consequence of these differences, the $\text{H}\alpha$ and $[\text{O III}]$ distributions do not lie on the same surface in the data cube, which could have been possible despite the large discrepancies in total intensity. The data cubes are in fact consistent with the idea that the $\text{H}\alpha$ and $[\text{O III}]$ emission come from completely different shocks. For reasons of signal-to-noise and confusion, it is not possible to detect faint counterparts of the mutual emission distributions. Lacking an explanation for this behavior in terms of radiative-shock models, it would not seem to be completely warranted to determine shock parameters from total intensity line ratios. In particular, the presence of confusing kinematic components will always bias measured line ratios towards 1.

3. Interpretation

A supernova blast wave expanding into a uniform medium will, if radiative, produce a uniformly expanding shell of optically emitting gas. Since this is not seen in the Cygnus Loop, it seems necessary to invoke density fluctuations of some kind in order to explain the observations. In particular, the density fluctuations must take place over the same scale as the deviations from uniformity in the data, i.e. on all scales from the size of the Loop as a whole down to sub-arcseconds. Furthermore, the discrepancies between the $\text{H}\alpha$ and $[\text{O III}]$ distributions cannot be explained by current steady-shock models, so that the occurrence of incomplete cooling and recombination layers is indicated, but also the cooling instabilities giving rise to non-steady shocks may produce large deviations from uniformity and simple evolution.

Because the classical cloud picture of the Cygnus Loop has had considerable success in explaining a number of observational

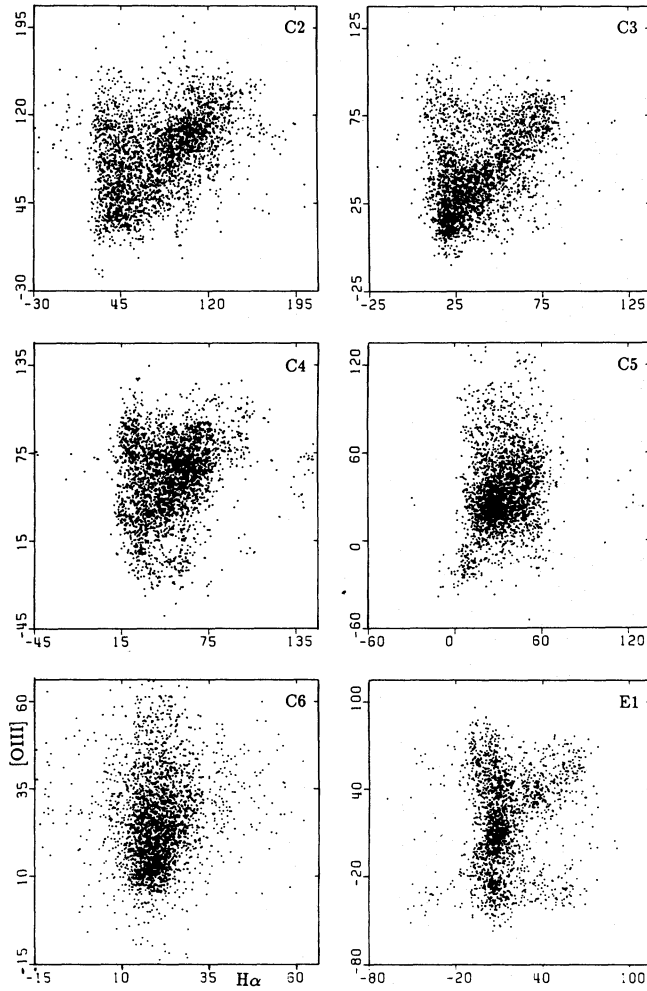


Fig. 3. Scatter diagrams of [O III] velocity (vertical axis) against H α velocity (horizontal axis); the profile mode v_a has been used (km s^{-1} LSR)

features (e.g. Fesen et al. 1982), it is worthwhile investigating whether the kinematics presented here also fit into this picture. For that purpose, we will first try to analyze the dynamics and the optical emission of the shocked gas in a cloudy medium. Subsequently, the observations will be interpreted in the context of the radiative-sheet model.

3.1. Cloud model

3.1.1. Radiative shocks

A number of authors have computed the structure and emission of radiative shocks, e.g. Raymond (1979), Shull & McKee (1979), Dopita et al. (1984), Cox & Raymond (1985). Assuming rapid equilibration between the electron and ion temperatures, the shock front itself can be regarded as thin with an adiabatic jump across. Immediately behind the shock any neutrals get ionized, thereby producing faint Balmer emission and lowering the post-shock temperature, a process which also takes place in a non-radiative shock. The face-on H α intensity associated with this is typically $I_{\text{H}\alpha}^{\text{rad}} \approx 2 \cdot 10^{-7} n_0(\text{H I}) v_{s7} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, with $n_0(\text{H I})$ the pre-shock neutral hydrogen density (cm^{-3}) and v_{s7} the shock speed in units of 100 km s^{-1} . Also [O III] $\lambda 5007$ emission is

produced at a level of $\sim 5\%$ of H α (Cox & Raymond 1985; Fesen & Itoh 1985). When the gas subsequently cools to about 10^4 K , it radiates predominantly in forbidden lines of high-ionization species. The [O III] intensity from this cooling zone (of column depth $\sim 10^{17} \text{ cm}^{-2}$) is approximated by $I_{5007}^{\text{rad}} \approx 2 \cdot 10^{-6} n_0 v_{s7}^{1.8} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ [with $n_0 (\text{cm}^{-3})$ the pre-shock density] for $v_s \gtrsim 90 \text{ km s}^{-1}$, and drops quickly below this shock speed; the exact value of this cutoff depends on the pre-shock ionization state. Behind this region is the recombination zone, which extends to a column depth of $\sim 5 \cdot 10^{18} \text{ cm}^{-2}$ as it is being photoionized by the emission from upstream. This is where the H α is produced, at an intensity of about

$$I_{\text{H}\alpha}^{\text{rad}} \approx 2 \cdot 10^{-6} n_0 v_{s7}^3 \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}. \quad (1)$$

These intensities have been parametrized from tabulated H β intensities and line ratios as a function of shock speed in model calculations of Raymond (1979), Shull & McKee (1979) and Shull et al. (in McKee 1987), and are rough approximations, valid for $v_s = 40\text{--}180 \text{ km s}^{-1}$. The actual numbers also depend on pre-shock ionization, magnetic field strength and abundances.

Taking into account the non-equilibrium ionization in the post-shock gas, McKee & Hollenbach (1980) estimate the cooling column for a strong shock in the range $v_{s7} = 0.6\text{--}10$ to be $N(T=10^4) = 2 \cdot 10^{17} v_{s7}^{4.2} \text{ cm}^{-2}$; hence, the cooling time equals

$$\tau = 1.5 \cdot 10^{-5} T_s^{1.6} n_s^{-1} \text{ yr}, \quad (2)$$

also for a weak shock, with post-shock temperature T_s (K) and density $n_s (\text{cm}^{-3})$.

3.1.2. Dynamics

As Falle (1988a, b) has noted, it is possible to get some idea of the evolution of the blast wave by looking at laboratory observations of adiabatic shocks hitting rigid bodies, simulating the interstellar domain of relatively weak shocks and large density contrasts; good examples are presented in van Dyke (1982). This can be complemented by analytical calculations (e.g. McKee & Cowie 1975), and by the results of numerical simulations (e.g. Woodward 1976; Rozyczka & Tenorio-Tagle 1987). Recent discussions have been given by Heathcote & Brand (1983) and McKee et al. (1987).

When the blast wave hits a cloud, the high post-shock pressure and the ram pressure of the post-shock flow will drive a transmitted shock into it, while a reflected shock, eventually developing into a bow shock, will be formed in front of the cloud if the density contrast is high enough (Fig. 4a). As the intercloud shock passes over the cloud, a diffracted shock (Mach stem) is formed that wraps around the cloud, where it collides with the shocks that have travelled around the other side, creating an expanding high-pressure region bordered by reflected shocks and topped with a Mach disk (Falle 1988b) (Fig. 4b). At a later stage, still more secondary shocks develop that are not drawn in the figure. The deflected shock continuing on behind the cloud will, together with the Mach disk, eventually straighten out into a plane shock wave. The exact behavior will depend, apart from the density contrast, on the nature of the shocks: adiabatic or radiative. As this may be different for the cloud and intercloud shocks there are four different cases, which will be discussed in the following.

To relate the blast wave and cloud shock speeds, the results of McKee & Cowie (1975) will be used, assuming that steady flow

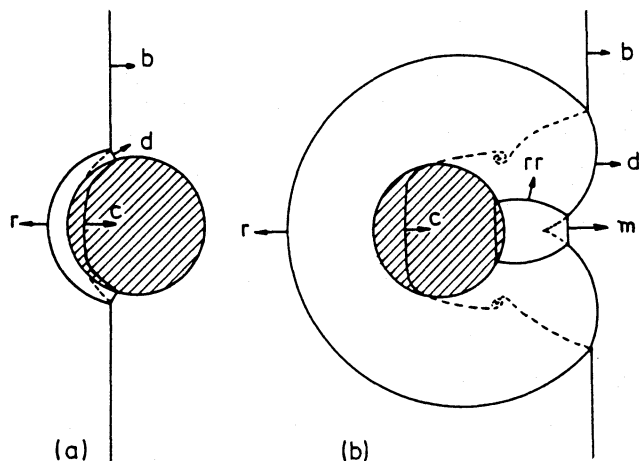


Fig. 4a and b. Schematic drawing of a shock hitting a cloud. **a** Early phase; **b** late phase. The shocks are: b – blast wave; r – reflected/bow; d – diffracted; rr – reflected at rear; m – mach disk at rear; c – cloud shock. Slip lines are dashed

has been set up, but that the pressure behind the blast wave has not yet significantly dropped off (their parameter $\beta = 1$).

3.1.3. Cloud shock

First, the behavior of a cloud shock driven by an adiabatic blast wave will be considered. On the assumption that the cloud shock is also adiabatic, the ratios of cloud/intercloud shock speed v_c/v_b and the cloud cooling times τ_c [using Eq. (2)] have been tabulated as a function of cloud/intercloud pre-shock density contrast ρ_c/ρ_b (Table 3, top part). The cloud cooling times are based on an X-ray derived blast wave speed of $v_b = 400 \text{ km s}^{-1}$ and pre-shock density of $n_b = 0.2 \text{ cm}^{-3}$, giving a blast wave cooling time of 0.26 Myr. As expected, the short cooling times indicate that the cloud shocks are radiative and as such better approximated as isothermal. The middle part of the table gives cloud/intercloud shock speed ratios, cooling times and cooling distances ($d_c = v_c \tau_c$) on the assumption that the cloud shock is radiative.

This case is the one numerically calculated by Woodward (1976). While the analytical treatment is valid only on the axis of

the cloud, these calculations show that the gradual decline in pressure accompanied by the faster flow around the cloud when going off-axis makes for an almost planar shock front moving into the cloud. When the blast wave has passed, the high-pressure region at the rear drives another shock into the back of the cloud, which is maintained by vortical flows that arise behind it. In the case Woodward considered, the speed of the second cloud shock moving from rear to front, also having a nearly planar shape, was $\sim 0.75v_c$. So for a fraction of time $t_2/(t_1+t_2) = (1-v_c/v_b)/(1+0.75v_c/v_b)$ (> 0.4 for $\rho_c/\rho_b \geq 5$), two plane shocks should be visible with spectral splitting $1.75v_c$ and $H\alpha$ intensity ratio $0.75^3 \sim 0.4$ [using Eq. (1)]. This kind of behavior is certainly not dominantly present in the data, although it may perhaps be recognized in e.g. the double [O III] profiles region in field C4; the strong arc crossing zero velocity on the west side, however, is not in accordance with this model. Nevertheless, there are some attractive features to this case. When the two inward moving shocks collide, the cooling layers are re-shocked and come to a near halt. While the shocks were moving inward, the flow around the cloud set up severe Kelvin–Helmholtz instabilities which are reinforced by Rayleigh–Taylor action, creating a complex shape and flow of the cooling cloud material. This can be combined with the idea that the clouds are not large enough to support complete cooling layers (Fesen et al. 1982), leading to the scenario in which the cloudlets light up in [O III] as the blast wave moves over them, while by the time they have cooled sufficiently to radiate predominantly in $H\alpha$, the bulk flow of emitting post-shock cloud gas has come to rest while the instabilities create broad line profiles. The incomplete radiative cloud model, that has previously been used to explain the difference in morphology between $H\alpha$ and [O III], is in this way also able to explain the kinematics: the appearance of the [O III] emission in the data cubes as deformed surfaces with some radial velocity–intensity correlation, and the $H\alpha$ morphology as more irregular and with little kinematic structure. No scalloped appearance is expected for the radiating clouds, and the optical filaments appear as sheets because the clouds merely trace out the blast wave. As the clouds are larger in some places, the cooling zone may become more complete and $H\alpha$ and [O III] filaments coincide. Known objections to this model are the large predicted size of the clouds (d_c in Table 3) and high predicted proper motion of the filaments; the objection from the current kinematical data is that in most places no backward-moving cloud shock is seen.

Table 3. Ratios of cloud shock over blast wave speed (v_c/v_b) and $H\alpha$ intensity (I_c/I_b), together with cloud shock cooling time (τ_c) and cooling distance (d_c), tabulated as a function of pre-shock density contrast (ρ_c/ρ_b). The top part is on the assumption that both shocks are adiabatic, with $v_b = 400 \text{ km s}^{-1}$ and intercloud pre-shock density $n_b = 0.2 \text{ cm}^{-3}$; the middle part for the same adiabatic blast wave driving a radiative cloud shock; the bottom part for both shocks radiative, with $v_b = 200 \text{ km s}^{-1}$

ρ_c/ρ_b	2	5	10	20	50	100
v_c/v_b	0.73	0.52	0.41	0.31	0.21	0.16
τ_c (yr)	48000	6700	1500	310	37	7.1
v_c/v_b	0.61	0.44	0.34	0.26	0.18	0.13
τ_c (yr)	28000	3700	820	180	22	4.2
d_c (cm)	$2 \cdot 10^{19}$	$2 \cdot 10^{18}$	$4 \cdot 10^{17}$	$6 \cdot 10^{16}$	$5 \cdot 10^{15}$	$7 \cdot 10^{14}$
v_c/v_b	0.90	0.85	0.80	0.74	0.64	0.55
I_c/I_b	1.4	3.0	5.1	7.9	13	17

3.1.4. Intercloud shock

Now turning to the behavior of the intercloud shock, first the adiabatic case will be considered. By definition, there will be no emission from the blast wave itself, but one can ask if the secondary shocks might be visible. The reflected shock is strongest for $\rho_c/\rho_b \gg 1$, in which case the Mach number of the reflected shock is $M_r = 3/\sqrt{5}$. The ratio of cooling times for the blast wave and the reflected shock is then $\tau_r/\tau_b = 1.4$; thus, the reflected shock does not become radiative either. The reflected shocks at the rear of the cloud are similar to the reflected shock in front in the sense that they also move through already shocked material, and in the same way the cooling times behind these are also longer than behind the blast wave. The Mach disk moves faster than the blast wave through the same gas and, hence, also has a longer cooling time. So, if the blast wave is adiabatic, all secondary intercloud shocks are adiabatic as well.

3.2. Sheet model

The interaction of a radiative blast wave with a cloud is more difficult to analyze. The way an *adiabatic* shock front propagates through a cloudy medium has been calculated recently by Norman et al. (1988); since the large-scale dynamics depend on v_c/v_b and the cloud spacing, the radiative case will not be very different when the shock is driven by the pressure in the hot remnant interior. The shock front is seen to wrap around the clouds, getting locally deflected by 90° or more depending on the exact locations of the clouds. The transmitted cloud shocks will be radiative as well, as cooling times through the denser material are shorter. In this case, v_c/v_b depends not only on ρ_c/ρ_b but also on the compression behind the blast wave. Taking this to be $77v_{b,7}$ (Shull 1988) and taking $v_b = 200 \text{ km s}^{-1}$, v_c/v_b is tabulated in the bottom part of Table 3. The ratios of H α intensities have been included, calculated from Eq. (1). From this, one may expect that in the case of a radiative blast wave running through a cloudy medium with low density contrasts ($\rho_c/\rho_b \lesssim 5$), cloud shocks will not show up prominently in the data cube; they will rather form part of a distorted radiative sheet, which is held backwards at the locations of the clouds. In a medium with high density contrasts, the cloud shocks will be dominant ($I_c/I_b \gg 1$); the visible shock fronts will be distorted to follow the shape of the clouds they traverse, because, like in the adiabatic case, they are driven by an outside intercloud shock that overruns the clouds. Again, one will observe a distorted radiative sheet; in this case, however, only within the individual clouds.

The radiative-sheet model was discussed by Hester (1987); large-scale distortions in the radiative sheet bring it near tangency with respect to the line of sight, where small-scale distortions create the impression of a network of filaments with a preferential, but not strictly maintained, orientation. The observed intensity I and radial velocity v arise by projection from the face-on values I_n and v_n : $I = I_n/\cos \alpha$, $v = v_n \cos \alpha$, with α the local angle between v_n and the line of sight (Fig. 5a). This means that for an infinitely narrow beam crossing the sheet only once, the product $Iv = I_n v_n$ is constant if the conditions do not change along the shock, or more accurately, $I \propto v^{-1}$, bounded by $\sqrt{2R/\Delta} I_n$ at $v=0$ (with R the local radius of curvature of the sheet and Δ the normal thickness of the emitting zone), and with the lowest intensity $I = I_n$ occurring at $v = \pm v_n$ (Fig. 5b). However, a change of α within an observing beam, as well as multiple crossings, which are easily

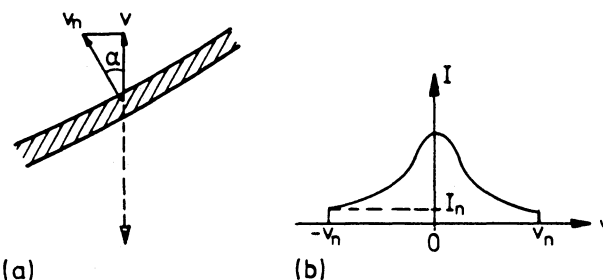


Fig. 5. **a** Orientation of shock front. **b** Relation between observed intensity and radial velocity (see text)

possible in a situation near tangency, will produce broader and more complicated profiles.

Hester (1987) presents model calculations for various examples of sheet geometry. Comparing his model position–velocity diagrams with the present observations, we find good qualitative agreement. In order to directly compare the profile parameter maps with the radiative-sheet model, several numerical simulations were run in which a thin, distorted shock-front section is projected in a position–velocity diagram, from which profile parameter cross-cuts are calculated. (This is similar to Hester’s modelling, who, however, fitted Gaussians to averaged model profiles.) Numerical values of sheet dimension, sampling distance, seeing, etc., were chosen to represent the current [O III] observations. Results of one typical case, a normally expanding, S-shaped sheet section, are shown in Figs. 6 and 7. Notable features in this simulation are: (1) instrumental and atmospheric smoothing obscures multiple components present in the profiles; (2) spatial smoothing not only broadens the profiles, but also substantially shifts them in velocity; (3) the broadest profiles are found on the shoulders of the filament.

While these models can serve as a guide in the assessment of the observations, significant deviations should be expected, caused by changes in detailed geometry, expansion velocity, and local intensity. It should be possible to tune this model to fit any local cross-cut through the observed data by choosing a suitable geometry of, and intensity distribution along, an arbitrarily complex radiative sheet. But such a quantitative comparison is not very interesting without a comprehensive physical model, linking geometry, local shock velocity, and intensity along the sheet; this will not be attempted here. In a qualitative sense, the essential characteristics of the morphology in the model data cube, viz. a continuous, often cusp-like sheet with diffuse emission at higher velocities and filaments closer to zero velocity, and the anticorrelation between intensity and velocity, are generally seen in the observations of the [O III] emission. The scatter diagrams that show the measured relation between intensity and radial velocity (Fig. 1) do not lie on the model relation of Fig. 5b, but rather have that as their envelope. This may be explained by a complex geometry with multiple crossings, biasing the average profile velocity towards zero.

Interpreting the [O III] observations in this way, there are some interesting consequences. In the first place, the predominantly positive radial velocities for the diffuse emission imply that the carrot is on the rear surface of the Cygnus Loop, expanding away from us. Secondly, the concentration of filaments and the

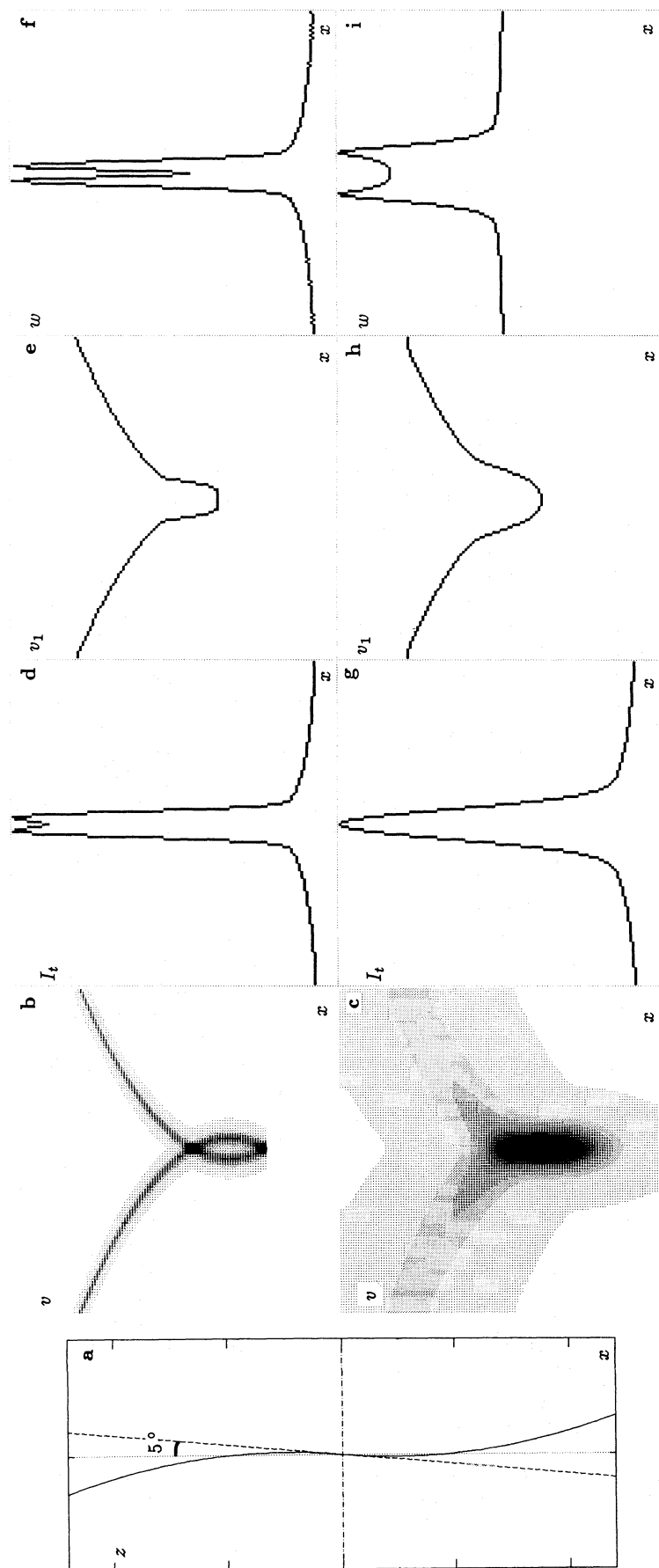


Fig. 6. Simulated observation of a small section of an expanding thin radiative sheet, which is locally deformed into an S-shaped undulation. The S consists of two adjoining circular arcs with $540''$ radius (one-tenth the radius of the Cygnus Loop); it overshoots the line of sight (z) by 5° . Local gas velocity is taken to be 150 km s^{-1} normal to the sheet. **a** The imaged section of the sheet; translational symmetry out of the paper. **b** Position-velocity diagram as imaged by a slit along the x-axis under $2''$ FWHM seeing, in bins of $0''.5 \times 0.88 \text{ km s}^{-1}$. **c** Smoothed position-velocity diagram. The smoothing is to 20 km s^{-1} by $5''.5$ FWHM, the resolution of the [O III] observations. **d-f** Profile parameters (integral I_t , mean velocity v_1 , equivalent width w) extracted from **b**. **g-i** Profile parameters (I_t , v_1 , w) extracted from **c**. The extent of the x-axis is $64''$ in all plots. The range of the velocity axis is -37.5 to 75 km s^{-1} ; in plots **b**, **c**, **e**, and **h** plot **i** is scaled between 0 and 43.5 km s^{-1}

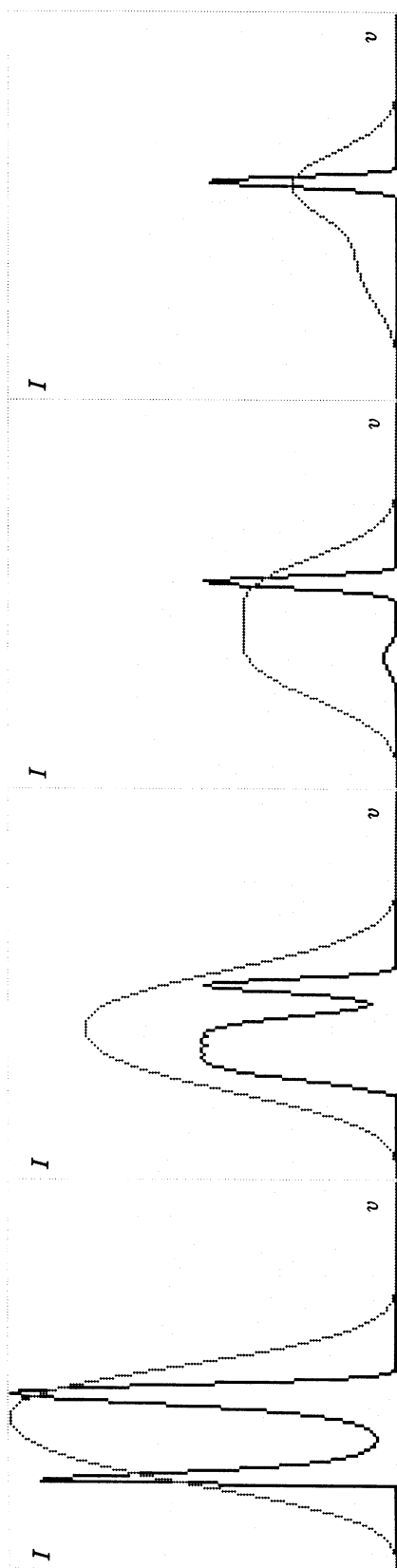


Fig. 7. Sample profiles from the synthetic position-velocity diagrams of Fig. 6, the first one taken at the central x location and the following ones at consecutive offsets of $2''$. Thick profiles are from the unsmoothed, thin ones from the smoothed data

occurrence of zero-radial-velocity crossings imply that the carrot is a region which is tilted as a whole towards tangency, although it is not near the edge of the Loop; moreover, the large velocity splitting in the areas of double profiles in fields C4 and C5 (v goes up to the expected value for v_n , implying a near-normal orientation of the shock front) clearly shows that the sheet doubles back for quite some distance, indicating a relatively large amplitude for its deformations. Thirdly, field E1 shows much the same structure as the others (but more complicated), although it is on the edge of the remnant. The high velocities attained in the double-profile regions between the filaments here too indicate the presence of large-amplitude deformations in the shock front. Finally, in many of the areas where the intensity-velocity correlation breaks down, this may be explained by a complex geometry; in some areas however, notably field C6, this explanation does not seem adequate.

3.3. $H\alpha$ kinematics

The different kinematical character of the $H\alpha$ emission makes it difficult to incorporate it into the sheet model. The differences in morphology have been explained by incomplete cooling and recombination zones, but to explain the kinematics it is in addition necessary to find a mechanism that rids the $H\alpha$ gas of its post-shock flow, or alternatively to postulate that the $[O\text{ III}]$ and $H\alpha$ emission arise in completely different shocks. For either idea, one may again turn to the blast-wave-cloud interaction, and consider the secondary shocks. Those within the cloud have been discussed before (Sect. 3.1.3), and were found to have the desired effect (but with objections), at least numerically confirmed for the adiabatic blast wave case. In addition, the much shorter cooling times and lower shock velocity in a cloud will preferentially produce $H\alpha$ there. As far as the secondary shocks in the inter-cloud medium are concerned, if the cooling zone is short compared to the cloud size, the reflected shock will be in the hot remnant interior and hence non-radiative, in the same way as it was in the adiabatic blast wave case. If the cooling zone is long however, which is indicated in view of the incompleteness in the $[O\text{ III}]$ -producing intercloud shock, the reflected shock will be found in that cooling zone. This can no longer be treated using simple hydrodynamics, since in the recombination zone the magnetic pressure is important. But whether a reflected shock is formed or not, kinematically the cloud may have the right effect of diverting the $H\alpha$ -emitting gas from regular post-shock flow, probably creating turbulence and instabilities. The importance of the shock structure at the rear will be less than in the adiabatic case (Falle 1988b), but will come to resemble it as the cooling zone becomes longer. It may be expected that these shocks and the turbulence behind the cloud also act to break up the post-shock recombinging flow.

3.4. Profile width

The profile widths (cf. Table 2) of the filamentary/diffuse component in the present observations are somewhat larger than those of Doroshenko (1970), who finds in $H\alpha$ $40 \pm 15 \text{ km s}^{-1}$ in the filaments and $63 \pm 22 \text{ km s}^{-1}$ in the diffuse regions, and those of Shull et al. (1982), who find $30\text{--}60 \text{ km s}^{-1}$ on filaments both in $H\alpha$ and $[O\text{ III}]$. Apart from the effect that the FWHM values given in the present work may be overestimates (depending on the shape of the profile, see Paper I, Sect. 4); this may be caused by

both the spatially and spectrally larger beam sizes in the current observations. Doroshenko & Lozinskaya (1977) find an average $H\alpha$ profile width on filaments of about 60 km s^{-1} .

The intrinsic contributions to the profile width are thermal and, for $H\alpha$, fine-structure broadening. Taking the $H\alpha$ temperature to be the same as the $[N II]$ temperature (since they are produced at roughly the same distance behind the shock), its measured value is $\sim 12\,000 \text{ K}$ (Fesen et al. 1982, from line ratios) to $\sim 16\,000 \text{ K}$ (Shull et al. 1982, from thermal profile widths), giving a thermal width (FWHM) of $\sim 25 \text{ km s}^{-1}$. This dominates over the fine-structure broadening of 6.4 km s^{-1} (Dyson & Meaburn 1971). Measured $[O III]$ temperatures are $\sim 40\,000 \text{ K}$ (Fesen et al. 1982; Shull et al. 1982), corresponding to a width (FWHM) of $\sim 11 \text{ km s}^{-1}$.

In principle, a second cause of broadening is the integration along the line of sight of different radial velocities, projected from the same normal expansion velocity, through a curved sheet of finite thickness. (The model calculations of Figs. 6, 7 used a thin sheet.) However, it is easily shown that this produces a negligible contribution, except exactly on a tangential filament; only there the velocity dispersion by this effect may be up to a few tens of km s^{-1} for a thick sheet with a small radius of curvature. But observed filaments need not reach tangency (Hester 1987), and when they do, they will most probably overshoot, creating a complex geometry with multiple profiles.

A third source of broadening is the velocity gradient in the post-shock cooling zone; this will appear with a factor $\cos \alpha$ in the observations (Fig. 5a). In the $[O III]$ -emitting zone the velocity dispersion Δv varies from 6 km s^{-1} for a $v_s = 40 \text{ km s}^{-1}$ shock via a maximum of 23 km s^{-1} for $v_s = 100 \text{ km s}^{-1}$ to 12 km s^{-1} for $v_s = 200 \text{ km s}^{-1}$, considering that the $[O III]$ zone is between temperatures $\min(T_s, 150\,000)$ to $10\,000 \text{ K}$, the compression is proportional to T^{-1} limited magnetically by $77v_{s7}$ (Shull 1988), and $\Delta v/v_s = 1 - \text{compression}^{-1}$. However, not all of this region will contribute equally to the flux, so the expected profile broadening will be less. The broadening in $H\alpha$ by this effect is $\lesssim 2 \text{ km s}^{-1}$, as in the recombination zone little extra compression takes place.

These considerations indicate that in $[O III]$ a correlation between intensity and velocity width might be expected, with profile widths of $\sim 12 \text{ km s}^{-1}$ in the filaments up to $\lesssim 25 \text{ km s}^{-1}$ in the diffuse emission. This is assuming that the geometry is simple, the observing beam is much narrower than the typical projected local radius of curvature of the shock front, and the shock velocity is not too high or too low. In the observations this correlation is only partly present, but moreover the observed widths are much larger than these, even taking into account the presence of the broad component. This can be explained by the presence of significant curvature in the shock front within one observing beam, which is indeed expected as at a resolution higher than the present $6''$ the filaments show considerable substructure. The large observed profile widths along the edges of filaments may also partly be explained by the large velocity dispersion within the beam as the sheet curves into tangency. But although this effect was demonstrated by the modelling of Figs. 6 and 7, it may not be enough: Fig. 6i shows a maximum width of only 43.5 km s^{-1} on the filament shoulders, 20% higher than on top of the filament. This contrasts with e.g. field C4 (Fig. 15, Paper I), where widths along filament edges go up to 100 km s^{-1} , a factor of two greater than widths on the filaments. To explain such high values, it seems necessary to invoke multiple crossings

of the line of sight through various parts of the sheet at different inclinations (other than resulting from the simple geometries like the S-model). Alternatively, the large $[O III]$ dispersions may signal the onset of turbulence in the cooling flow, which will eventually dominate the kinematics of the $H\alpha$. Finally, an overestimate of the instrumental resolution would explain the fact that no unresolved nebular profiles are seen (cf. the scatter plots of Fig. 2), but would leave intact the large range of the measured widths.

In $H\alpha$, profile widths would be expected to be $\sim 27 \text{ km s}^{-1}$ everywhere (in a narrow beam), dominated by thermal broadening. Much broader profiles are actually observed, with a partial correlation between intensity and width in the sense that the brightest filaments have the narrowest profiles (Fig. 2). The very high values have been explained by the presence of the underlying broad component, but even in the bright filaments the width is still $\sim 50 \text{ km s}^{-1}$ (Table 2), much greater than expected for regular post-shock flow with a simple geometry. These broad profiles and the fact that spatial velocity gradients are seen to be not very large in $H\alpha$, indicate the presence of much unresolved velocity structure in the data, even more than for the $[O III]$ -emitting gas. This structure may either be in the form of a sheet, which in that case must be even more distorted than in $[O III]$, or the $H\alpha$ profile widths indicate the amount of turbulent velocity in the recombining gas.

3.5. Broad component

A broad background component was also detected in $H\alpha$ by Doroshenko & Lozinskaya (1977), who find emission in the range -100 ± 80 to $\gtrsim 100 \text{ km s}^{-1}$ (varying with position) at an intensity of 5–8% of the filaments. Shull et al. (1982) also report an occasional component of width $120\text{--}170 \text{ km s}^{-1}$, best seen in IC 443 (another evolved supernova remnant) at a level comparable to that of their narrow components. The highest absolute $H\alpha$ velocities are measured by Kirshner & Taylor (1976), -100 to -270 km s^{-1} ; these are attributed to emission from the non-radiative shocks (Raymond et al. 1980).

The measured $H\alpha$ intensity of this latter emission in the Cygnus Loop is ~ 2 (in units of $10^{-6} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$) where it is diffuse and up to ~ 20 times as bright in filaments (see also Raymond et al. 1983; Hester et al. 1986). The intensity that is measured here for the broad, diffuse component is ~ 12 (corrected for $E(B-V)=0.08^m$). Furthermore, these extreme velocities are not seen in the present data. There is of course the uncertainty of interference order, which makes the velocity only determined modulus the free spectral range of 371 km s^{-1} ; however, the broad component is always centered around $\sim 60 \text{ km s}^{-1}$ and appears to be contained within one free spectral range. Moreover, the broad component in $[O III]$ is seen at an intensity ~ 8 , while the $[O III]$ emission from the non-radiative shock is only $\sim 5\%$ of $H\alpha$ (Fesen & Itoh 1985). This indicates that the broad component in the present data does not arise in non-radiative shocks.

Since it is not really above the noise level at the resolution used in the analysis, and smoothing causes the diffuse/filamentary component to blend in and dominate, it is not possible to thoroughly analyze the broad component at the present sensitivity. In many places, the diffuse component merges in with the broad component, and the latter cannot be morphologically distinguished from a complex diffuse region. Thus, in the context of the radiative-sheet model, it is possible that this component

arises from faint sections of the sheet, for which a complex geometry is then implied; the front side of the Cygnus Loop may also contribute. The high-velocity extent of the emission would then imply rather large shock velocities, close to the radiative limit of 200 km s^{-1} . This kind of structure could be similar to “blisters”, as have been proposed to exist in the Vela remnant (Meaburn et al. 1988); no well-defined examples of individual blisters are found in the data, however. We may also be seeing the radiative intercloud shocks in a medium of high density contrasts that were discussed in Sect. 3.2. Alternatively, turbulence in the post-shock gas, or weak secondary shocks may play a role. Also an origin inside the remnant, not connected with the present-day outer blast wave, is conceivable. Finally, a purely thermal origin cannot be reconciled with the nearly equal values for the broadening in $\text{H}\alpha$ and $[\text{O III}]$.

3.6. Narrow $[\text{O III}]$ component

The constant near-zero radial velocity and small (unresolved) width of the narrow $[\text{O III}]$ component imply that it does not arise in the post-shock flow. It only occurs, however, at locations where shocked $[\text{O III}]$ is seen. This indicates that the emission may come from photoionized gas in the precursor region. Shull (1983) finds the same kind of $[\text{O III}]$ emission in the LMC remnant N 49, and detects it in other lines as well, including $\text{H}\alpha$; he finds the relative line intensities to be consistent with a photoionized nature. In view of this, it is possible that the $\text{H}\alpha$ emission that in this study has been attributed to a geocoronal origin contains a (possibly even dominant) photoionized remnant contribution. The radial velocity, near 12 km s^{-1} LSR, is consistent with that in the $[\text{O III}]$ component. (In the case of N 49, no such confusion arises because the systemic velocity of the LMC shifts the emission away from the geocoronal line.)

There is one region in field C4 where this component has a width of $\sim 40 \text{ km s}^{-1}$, but still centered at its normal velocity (Paper I, Fig. 13). The interpretation is somewhat problematic: a thermal origin implies a temperature of $5 \cdot 10^6 \text{ K}$; a turbulent origin is hard to reconcile with its undisturbed mean velocity. Perhaps a mechanism similar to that producing the non-radiative Balmer emission is at work here; the temperature corresponds to a shock speed of 190 km s^{-1} . Alternatively, this may be a region that was disturbed by a previous, unrelated event, or background emission.

It is interesting to note that the kinematical character of N 49 is very similar to that of the Cygnus Loop in many other respects. When the position-velocity diagrams presented in Paper I are smoothed to a much lower spatial resolution, they look very much like those of N 49 in Shull (1983).

3.7. Non-steady shocks

In fast radiative shocks, the cooling time scale can be much less than the dynamical time scale. This results in thermal instability and catastrophic cooling, giving rise to secondary shocks within the cooling zone (Falle 1981). The occurrence of the instability depends on the slope of the cooling curve, which for a supernova remnant does not have the same form as in the equilibrium case since heating and cooling time scales are shorter than ionization and recombination time scales in the shocked gas. Numerical calculations of fast radiative shocks show a complex but periodic evolution, with a strongly oscillating primary shock speed, and

repeated development and decay of secondary shocks that move both in the upstream and downstream directions (Innes 1988; Gaetz et al. 1988; Innes et al. 1987a). The instability seems to occur for shock speeds $\gtrsim 140 \text{ km s}^{-1}$. $[\text{O III}] \lambda 5007$ model profiles calculated by Innes et al. (1987b) show that a $v_s = 200 \text{ km s}^{-1}$ shock encountering a simple density perturbation will show two to three components of comparable intensity (near v_s and near $0.5v_s$) during much of the time; with more realistic perturbations more complex profiles are possible. A 150 km s^{-1} shock, also unsteady, would show less dramatic effects.

In the current data, this kind of $[\text{O III}]$ profile is not seen. Most $[\text{O III}]$ profiles in diffuse emission regions are simple, and the double ones mostly have one component at positive and one at negative velocities. This may indicate that radiative-shock speeds in the Cygnus Loop are not much larger than 140 km s^{-1} , but this limit is brought into question by Smith (1989), who has tried to estimate the effect of a magnetic field on the occurrence of secondary shocks and concludes that they may be damped for shock speeds up to 200 km s^{-1} , depending (again) on the exact shape of the cooling curve and the field strength. On the other hand, the prominently double $[\text{O III}]$ profiles are only generated in a relatively late phase of the evolution of the shock's instability; before $[\text{O III}]$ emission from the secondary shocks becomes important, the primary-shock velocity has already oscillated over more than a factor of two and line ratios have varied over a large range. The $[\text{O III}]$ kinematics observed here do not therefore prove that the radiative shock in the Cygnus Loop is steady, so secondary shocks due to cooling instabilities may be responsible for the $\text{H}\alpha$ kinematics or for the broad background component.

3.8. Systemic velocity and distance

The presence of photoionized components to the emission provides a means to estimate the systemic velocity of the Cygnus Loop. The narrow $[\text{O III}]$ component is found at $5 \pm 2 \text{ km s}^{-1}$ (LSR) in field C2 and at $10 \pm 3 \text{ km s}^{-1}$ in field C4. If this emission is from photoionized gas, its $\text{H}\alpha$ must be present near 12 km s^{-1} (LSR) in order to blend with the geocoronal line. From this, the systemic velocity of the Cygnus Loop is estimated at $8 \pm 3 \text{ km s}^{-1}$ (LSR). This value is consistent with the velocity of H I ($0\text{--}10 \text{ km s}^{-1}$) found adjacent to the remnant by DeNoyer (1975) which she associated with it, as well as the velocity of CO ($9\text{--}12 \text{ km s}^{-1}$) found along the western edge (Scoville et al. 1977), strengthening our interpretation. The velocity is considerably lower than the 33 km s^{-1} found by Minkowski (1958) and Doroshenko (1970). Their value was derived, however, from fitting a velocity ellipse to a radius-velocity diagram of the Cygnus Loop as a whole, while the present data indicate that the small-scale structure dominates in producing observed radial velocities. This also explains the poor fit of an ellipse to their data, especially obvious in Doroshenko's graph which has many more data points. Using values from Allen (1976), the systemic velocity yields a kinematic distance of $1.3 \pm 0.7 \text{ kpc}$ for the Cygnus Loop, not inconsistent with the generally accepted distance of 770 pc .

The highest radial $[\text{O III}]$ velocities measured between the filaments go up to 150 km s^{-1} and even 180 km s^{-1} in one place (field C5), considerably higher than the expansion velocity derived by Minkowski and Doroshenko of 110 km s^{-1} . In view of the importance of the small-scale kinematic structure, a well-defined value for the overall expansion of the Loop is hard to give. Using 180 km s^{-1} instead of 110 km s^{-1} in connection with the

proper motion of $0.03'' \text{ yr}^{-1}$ as derived for the bright eastern and western edges of the Loop (Hubble 1937) would give a distance of 1300 pc instead of 770 pc. However, this very large radial velocity may represent a region of locally high shock speed, and for neither this diffuse region nor for the filaments on the remnant's edge is the exact orientation of the shock speed with respect to the line of sight known. It would be very interesting to have proper motion measurements of the [O III] filaments in the fields that have been observed in this study.

4. Conclusions

The optical kinematics observed in selected regions of the Cygnus Loop bear a greater resemblance to the radiative-sheet model, to which the [O III] emission in particular is seen to conform rather well, than to models in which clouds dominate in shaping the filaments. In the context of this model, the kinematical patterns in the data imply quite large distortions for the shock front, which may assume this shape indirectly by the presence of clouds or density inhomogeneities in the surrounding medium. The broad background component found in the data may then be interpreted as emission from faint sections of the sheet with a complex geometry, or, alternatively, as the result of post-shock turbulence or weak secondary shocks. Although the sheet model generally describes the data very well, at a number of locations a very poor radial velocity–intensity correlation makes its application somewhat problematic. It should also be noted that although the [O III] kinematics are best characterized by the sheet model, the major feature, that of low velocities where the emission is brightest, would also be found to some extent in the scenario in which the filaments are shocked clouds, since the higher gas density in the clouds leads to lower shock speeds.

In order to explain the different kinematics and morphology of the $H\alpha$ emission, it is necessary to invoke mechanisms that rid the recombining gas of its regular post-shock flow. These mechanisms may be found in the presence of clouds, creating secondary shocks and turbulence, or alternatively in (catastrophic) cooling instabilities, which have the same effects. Of course, another possibility is that the two lines emanate from completely different shocks; a radiative-sheet model for the $H\alpha$ emission is possible when that sheet has much more detailed, hence more unresolved, structure than the [O III] sheet. The occurrence of non-steady shocks is not indicated by the present observations, but is not ruled out either.

The narrow [O III] component seen almost everywhere, which is similar to a component observed in the SNR N 49, probably originates in photoionized gas in the precursor region. It may also be present in $H\alpha$, though masked by geocoronal emission, and the fact that $H\text{ I}$ emission from gas believed to be adjacent to the Cygnus Loop has the same LSR velocity also supports the association. This unaccelerated component enables us to estimate the systemic velocity of the Cygnus Loop environment: $8 \pm 3 \text{ km s}^{-1}$ LSR. Based on the usual Galaxy kinematics, this corresponds to a distance of $1.3 \pm 0.7 \text{ kpc}$, somewhat higher than, though not in conflict with, the widely quoted value of 770 pc. In one location, this [O III] component broadens to $\sim 40 \text{ km s}^{-1}$, possibly resulting from a mechanism similar to that producing non-radiative Balmer emission.

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