NEW OBSERVATIONS OF NON-RADIATIVE SHOCKS IN THE CYGNUS LOOP

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ABSTRACT: We present deep Hα and [O III] images and echelle spectra of non-radiative shocks in the NE Cygnus Loop. The contrast between the smooth Hα structure and the clumpier [O III] indicates that portions of the sheet-like front are beginning to go radiative. The column depth through the shock seems to be $\leqslant 10^{17.5}$ cm^{-2} for the entire region -- a remarkable constraint for such a large structure.

INTRODUCTION: The Balmer-line emission from non-radiative shocks arises in a zone of collisional excitation immediately behind the shock front. The Hα line profile shows both narrow and broad components with widths related to the pre- and post-shock temperatures, respectively. From such a profile, Raymond *et al.* (1983, hereafter RBFG) derived a shock velocity of order 200 km s^{-1} for one position. The strength of forbidden line emission, particularly the presence of [N II] and [S II] in a spectrum presented by Fesen and Itoh (1985), seems to require some radiative contribution to the emission. An Hα image presented by Hester, Raymond, and Danielson (1986, hereafter HRD) shows the two faint filaments just visible on the POSS red print to be part of a continuous band of very sharp filaments and diffuse emission.

OBSERVATIONS: Images of a field centered on the two brightest filaments were obtained through a 15Å FWHM Hα filter and a 30Å FWHM [O III] λ5007 filter using a new reimaging camera at the 60" telescope at Palomar Observatory. The camera system employs a 306 mm collimator, a 58 mm camera lens, and a spherical field lens to put a 16′ X 16′ field onto an 800 X 800 pixel TI CCD at 1.2 arcsec pixel^{-1} with an effective speed of f/1.65. This camera covers a field with about 5 times the area of the system used by HRD.

The images were calibrated using the spectrophotometry of RBFG. Hα/Hβ was assumed to be 3 (close to the value of 2.8 reported by Fesen and Itoh). The Hα image is a single 3000 s exposure with a detection threshhold (2σ in a 3 X 3 pixel sample) of 3×10^{-7} ergs cm^{-2} s^{-1} sr^{-1} (which would correspond to an emission measure of ~ 3.5 at T = 10^4 K). The [O III] image is a stack of a 10000 s and a 6000 s exposure, and has a detection threshhold of 1.5×10^{-7} ergs cm^{-2} s^{-1} sr^{-1}. The background is nonuniform in the [O III] frame due to charge transfer problems associated with a bright star in the field. Dot density representations of the images are presented in Figure 1, along with Einstein HRI data. (The coverage of the X-ray data is incomplete in the northern part of the field.) An enlargement of an approximately 2′ square region just south of the center of the field is shown in Figure 2. Contours of [O III] are superposed on a dot-density representation of Hα.

https://doi.org/10.1017/S0252921100102775 Published online by Cambridge University Press

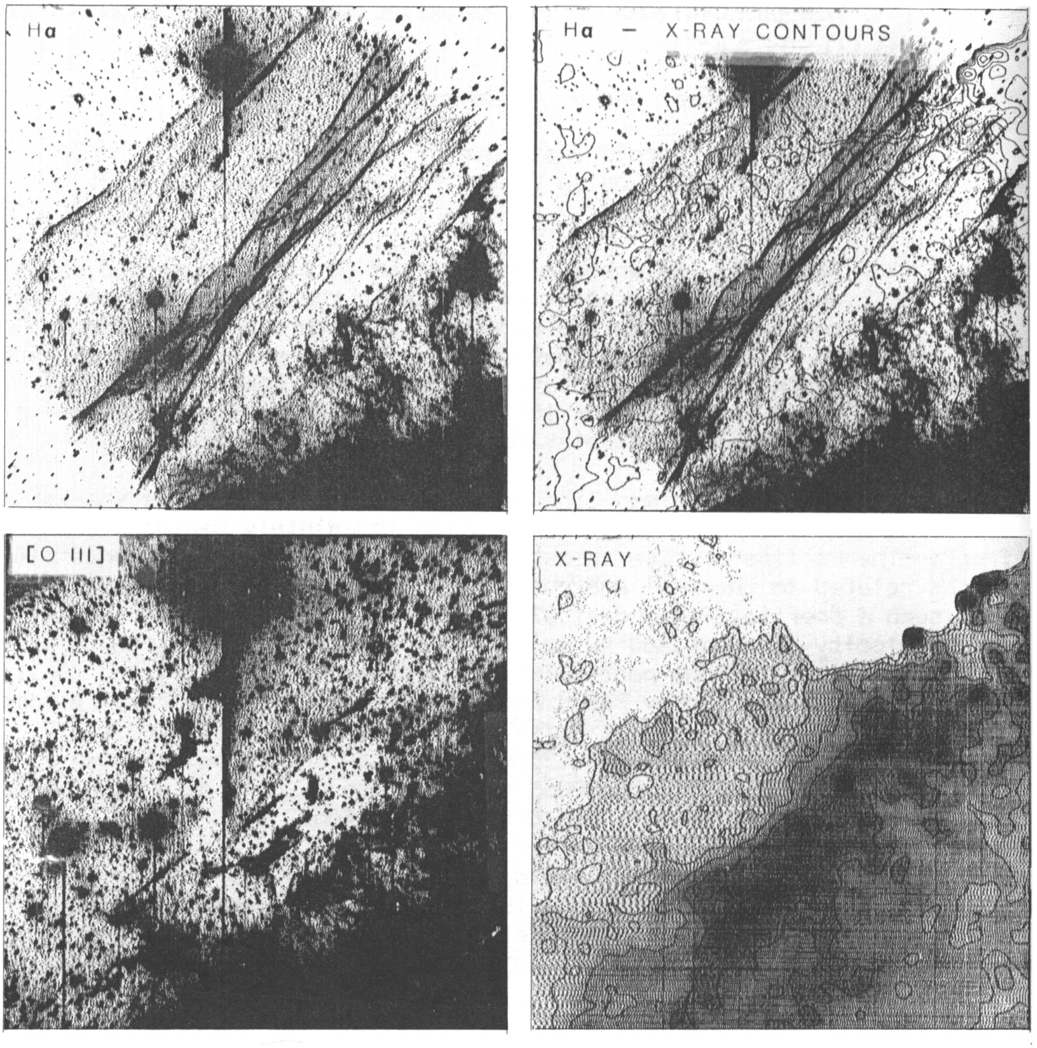

Figure 1.

High resolution spectra were obtained for several positions using the echelle spectrograph on the 4-m telescope at Kitt Peak. The spectrograph was used in a long slit mode, with an optical flat replacing the cross disperser and order separation obtained with a narrow band filter. Figure 3 shows Hα line profiles for the leading and trailing filaments in Figure 2, labelled position 1 and 2, respectively.

RESULTS: The extent, smoothness, and continuity of the Hα emission is the most immediate result. The relative brightness of the diffuse Hα emission in the three regions bounded by lines of prominent filaments can be explained by a single sheet of emission (cf., Hester 1987). From the perspective of the observer the sheet appears to extend from the bright radiative emission to the second line of non-radiative filaments,

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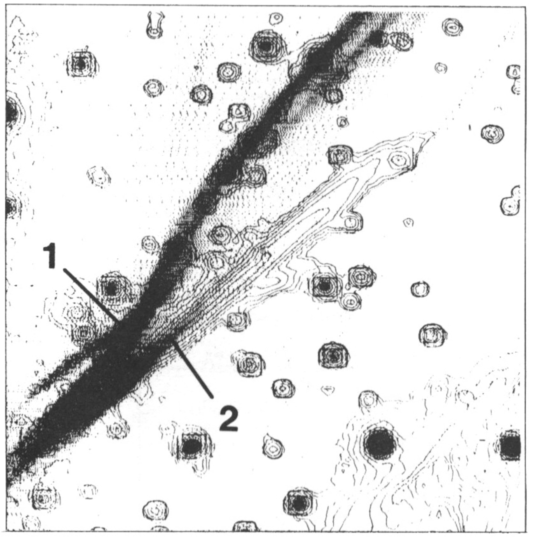

Figure 2

double back and again reach tangency at the line of filaments ~ 1-2′ to the SW, and from there extend to the outermost tangency ~ 7′ to the NE. Regions of X-ray emission are bounded by lines of optical filaments (cf., Hester and Cox 1986). This includes filaments in the extreme NE (outside of the field of HRD) which bound the X-ray "halo" reported by Ku *et al.* (1984). The X-ray brightness is roughly correlated with the surface brightness of the Hα filaments that it trails.

The FWHM of the broad component at position 1 is 163 km s^{-1}. The width of the trailing filament (2) is 116 km s^{-1}. All other positions observed had velocities in the 115 - 130 km s^{-1} range. The position with the broadest Hα is also the least pronounced in [O III]. With the exception of position 1, these widths are less than the 160 km s^{-1} width reported by RBFG. A higher signal to noise spectrum of their position was obtained, and yielded a velocity width of 133 km s^{-1}. Observation of a smaller width and evidence below suggesting that some of the [O III] emission is due to a radiative contribution weakens arguments in RBFG favoring Coulomb equilibration behind the shock. In fact, the shock velocity of ~ 120 - 130 km s^{-1} inferred from the present data assuming Coulomb equilibration is uncomfortably small. We prefer a shock velocity of 160 km s^{-1}, consistent with rapid equilibration. For position 1, this gives $v_s \approx 200$ km s^{-1}.

The [O III] emission is dominated by a few bright regions where [O III]/Hβ can exceed 100. These are clearly portions of the shock that are going radiative. Ignoring these, [O III]/Hβ has a fairly uniform value of ~ 0.1 for filaments which are bright enough to be seen in [O III]. The brightest (and therefore best studied) Hα filaments are atypical in that they lie in close proximity to regions of bright [O III]. The optical spectrum of RBFG has [O III]/Hβ ~ 50% higher than average for faint [O III] filaments.

In Figure 2, [O III] strengthens along a filament as Hα weakens. Preliminary models support the interpretation that as progressively more of the [O III] zone forms, the UV from the shock will preionize hydrogen. For a 160 km s^{-1} shock in a medium that was originally 30% neutral, this occurs at a column density of ~ 10^{17} - $10^{17.5}$ cm^{-2}. This corresponds to a time scale of ~ 200 - 700 years, during which time the shock will have travelled ~ .03 - 0.1 pc, or a distance of ~ 10" - 30" on the sky. While very strong magnetic support behind the shock may increase these distances by as much as a factor of ~ 3, the fact remains that over a very short time scale (a few hundred years) the shock newly encountered material with density ~ 1 cm^{-3} over a surface with an area

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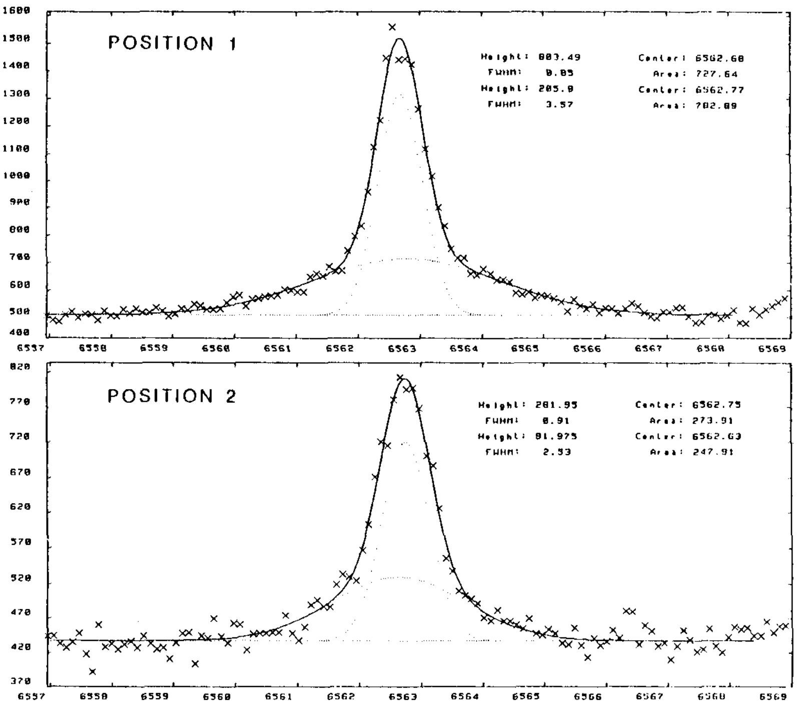

Figure 3

of order 100 pc^2. Furthermore, this surface has a significant curvature that fits well with the outline of the rest of the remnant.

We cautiously suggest that these observations could be most easily understood if the Cygnus Loop were the result of a cavity explosion. The presence of bright X-ray emission immediately interior to shocks that do not seem to be fast enough to produce the X-rays also indicates that the shock has recently undergone rapid deceleration over a large area. Finally, the remarkably smooth morphology of the emission (despite evidence that shock velocities vary significantly in the region) is easier to understand if the denser more inhomogeneous medium were encountered only recently.

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