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Abstract

The one dimensional distribution of [Fe XIV] λ5303Å emission has been determined along a radius of the Cygnus Loop through the use of a tilting filter photometer. The observed emission extends at least 5 arc minutes outside the optical filaments. A simple Sedov solution model of the temperature and density distribution behind the shock agrees with the observations if the shock front is near the outer extent of the [Fe XIV] emission, the shock velocity is from 300 to 250 kms^{-1} and the density external to the remnant is about 0.7-1.4 cm^{-3}. These parameters are in reasonable agreement with X-ray maps and optical radial velocities.

I. Introduction

This work concerns the relation between the shock in the interstellar gas and the observed X-ray and optical emission of the Cygnus Loop. Following the discovery of X-rays from the Cygnus Loop by Grader, Hill, and Stoering (1970) and subsequent determinations that the X-rays were likely to have a thermal origin (Gorenstein et al 1971, Tucker 1971), attempts were made to observe the [Fe XIV] λ5303 emission that should accompany thermal X-rays. Kurtz, Vanden Bout and Angel (1972) searched for the emission and it was detected by Woodgate et.al. (1974). Those observations were consistent with a thermal origin for both the X-rays and the [Fe XIV] with a temperature of $2.8 \pm 0.3 \times 10^6$K, and a normal abundance of iron relative to C, O, Si and S, the elements whose lines are responsible for most of the X-ray emission (Woodgate, Angel, and Kirshner (1975)).

The high temperature was puzzling because the radial velocity measurements of Minkowski (1958) made from optical emission lines in bright filaments gave an expansion of about 116 kms^{-1}, which gives a post-shock temperature of order 3.5×10^5K. This numerical difficulty evaporated with the discovery by Kirshner and Taylor (1976) of Hα emission at velocities up to 300 kms^{-1}. However, the connection between the shock front, the hot gas and the optical filaments remained unclear. In particular, the alternative models for production of the hot gas - that of Tucker (1971), in which the hot gas is immediately behind the shock and that of Cox (1972) in which the hot interior is responsible for the X-rays and [Fe XIV] cannot be distinguished without moderately good spatial resolution.

II. Observations.

In order to determine whether the [Fe XIV] emission and the hot gas that produces it is located inside, outside or coincident with the optical filaments, measurements of the [FeXIV] flux were made in seven locations on a radial line passing through the bright optical filaments in the northeast segment of the loop (NGC 6992) as shown in Figure 1. The same observational techniques employed by Woodgate et.al. (1974) were used, except with the #1 0.9m telescope at KPNO rather than a 6-inch refractor.

The measurements consisted of differential photometric measurements through a 6 Å width filter centered at λ5303 and with the band shifted 15Å to the blue by tilting the filter. Measures were made on and off the source, and the excess counts on the source and in the band computed in the same way as before. The entrance aperture to the photometer measured 5'34" by 2'43" for a total solid angle of 1.28 x 10^{-6} sterad. Slight adjustments in the positions of the apertures were made to avoid bright stars.

Data were obtained on 6 photometric nights in May and August 1976. As illustrated schematically in Figure 2, the [Fe XIV] emission extends 5 arc min outside the "front" of the optical filaments. If the Loop is at the conventional (though perhaps unreliable, see Kirshner 1976) distance of 770 parsecs, this separation corresponds to about 1 parsec.

III. Interpretation

If the Cygnus Loop can be considered an adiabatic blast wave in a homogenious medium, then the similarity solution given by Sedov (1959) provides a description of the temperature and density as a function of radius in terms of the post-shock temperature, density and the shock radius. We have integrated along the line of sight through such spherical models to derive the expected surface brightness of [Fe XIV] emission as a function of radius. The parameters of the Sedov solution were provided in a convenient form by Roger Chevalier of KPNO and the atomic parameters for the λ5303 line were taken from Kurtz et al. (1972).

Curves of surface brightness versus radius are compared to the data in Figure 3. For velocities higher than 300 kms^{-1}, [Fe XIV] emission is produced most efficiently just behind the shock front, for example if v_s=350 kms^{-1} the surface brightness reaches a maximum at R/R_s= 0.96. For lower shock velocities, the maximum in [Fe XIV] surface brightness is farther toward the center because the temperature at which [Fe XIV] is best produced is higher than the temperature just behind the shock, and the temperature rises toward the inside in a Sedov solution. This effect is compounded by the increased path length through the sphere for small values of R/R_s. We found a reasonable match to the data of Figure 2 for shock velocities between 250 and 300 kms^{-1}. For lower velocities, the peak surface brightness was too broad and too far toward the inside to match the data, while for higher velocities, the peak was too narrow and too close to the outside. Both of the fits shown in Figure 3 fail to match the innermost point. The calculations always show a substantial [Fe XIV] surface brightness, even at R/R_s = 0 because the line of sight always traverses (twice!) the shell that represents the temperature at which [Fe XIV] is best produced (about 2.1×10^6K). The failure to reproduce this behavior must mean that the assumption of a homogenious sphere is defective. That is no surprise, since the distribution of X-rays over the surface of the Loop is far from uniform.

The peak surface brightness observed depends on the density of the ambient gas. For 300 kms^{-1}, the observed peak is matched for a pre-shock density of 0.7 cm^{-3}, and for 250 kms^{-1}, it is matched for a density of 1.4 cm^{-3}. For lower shock velocities, the required density becomes improbably large. With these parameters, the initial energy and the age can be derived. For 250 kms^{-1}, the energy is 8×10^{50} erg, and the age is 29,000 years. For 300 kms^{-1}, the numbers are 6×10^{50} erg and 24,000 years.

A scan was also made over the same fields of view by the same technique in the [Ar IV]λ4740 line. A positive detection was only made in patch (iv) (see Figure 1), where a surface brightness of $(18 \pm 4) \times 10^{-8}$ erg cm^{-2} s^{-1} sterad^{-1} was measured. All the other patches were weaker than 10×10^{-8} erg cm^{-2} s^{-1} sterad^{-1} (3σ). The emission appears in the outermost patch of the optical filaments.

Since the line is produced at about 10^5 °K, this observation is consistent with the hypothesis that the filaments are formed by instabilities caused by radiative cooling, (see McCray, Stein and Kafatos, 1975.)

IV. Discussion

Of course, it is possible that the location of the hot gas relative to the optical filaments and the shape of the [Fe XIV] distribution are purely accidental. However we do not believe this to be the case because of the good agreement between the parameters derived here and independent evidence from X-rays and other optical data. The X-ray map of Rappaport et.al. (1974) showed a slightly larger diameter for the X-rays than the optical filaments: 2°75 compared to 2°65. This agrees with our result that the hot gas seen in [Fe XIV] extends ~5' farther out than the optical edge. They also find that the overall distribution of the X-rays requires a shock velocity 400 ± 100 kms^{-1}, and a mean density of 0.25 ± 0.10cm^{-3}. Our results are more sensitive to the shock velocity since we fit the shape of the distribution, not just its radius. Our velocity of 300-250 kms^{-1} requires somewhat higher density to match the observed surface brightness than the high velocity models of Rappaport et.al. Although this could represent a local density fluctuation it is more likely to reflect the uncertainty in the parameters. We also note that the shock velocity required by the present data agrees well with the velocity of the Hα emission at 300 kms^{-1} found by Kirshner and Taylor (1976).

It will be extremely interesting to compare the present data with X-ray observations of high spatial resolution from HEAO and other new X-ray experiments. Even without detailed X-ray observations, it is clear that the direct interaction of the supernova shockwave with interstellar gas is more clearly tied to the high temperature phenomena of [Fe XIV] and X-ray emission than to the optical filaments.

We would like to thank R. Chevalier for providing us with the Sedov solution in a useable form, and Burt Johnson of KPNO for assistance with Forth.

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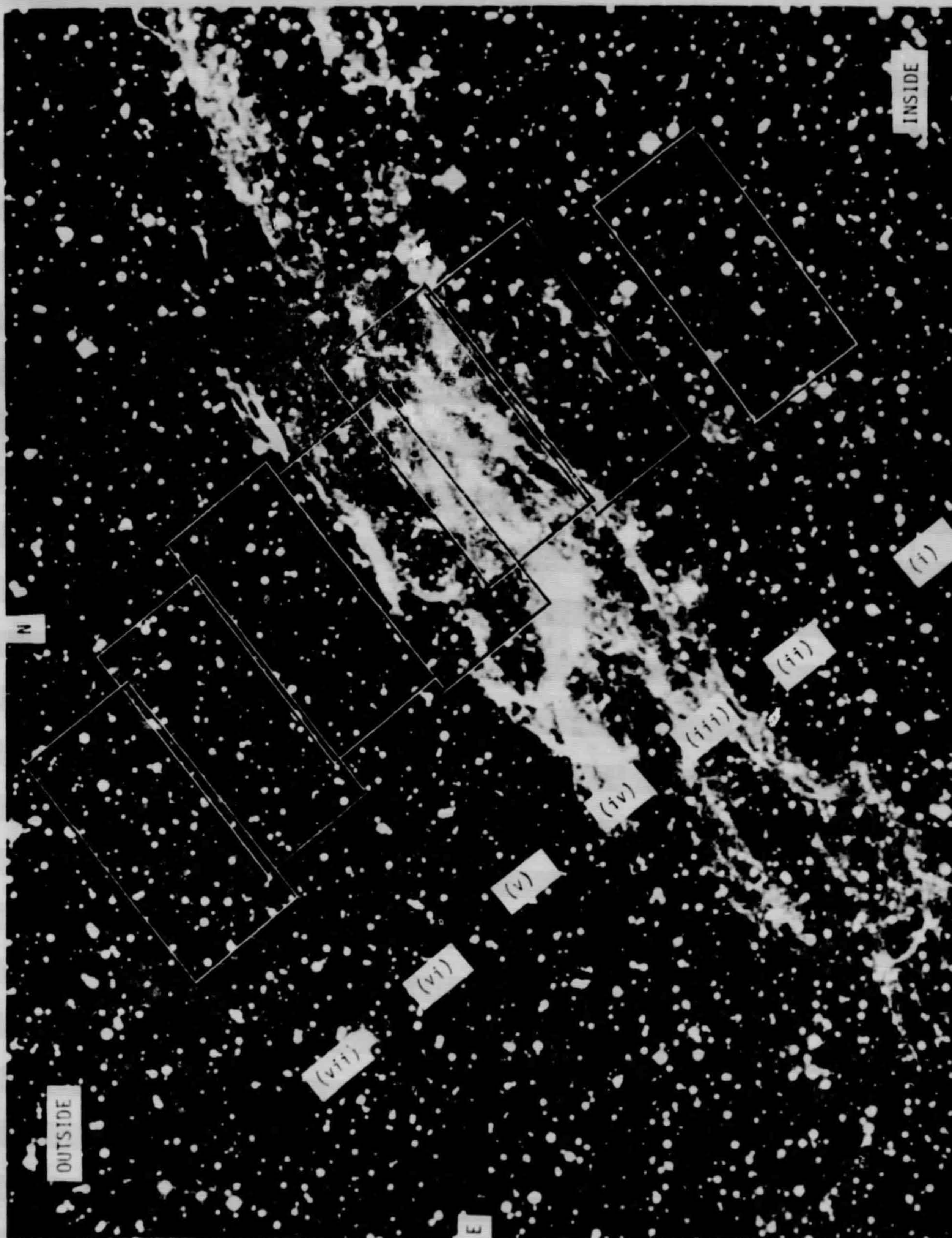
Figure Captions

Figure 1. Locations of the entrance apertures for the [Fe XIV] measures are shown. North is up, and east to the left. The apertures measure 5'34" by 2'43". The approximate position of the center aperture is (1950) 20^h55^m +31°30'.

Figure 2. Surface brightness in [Fe XIV]. The maximum surface brightness, S max, is 7.0 x 10^{-8} erg cm^{-2} s^{-1} sterad, about 3% of the night sky surface brightness in the 6 Å bandpass. The abscissa is the fractional radius R/R_s, where R_s is the shock radius, taken to be about 82'. The outside of the Loop is to the left, and the inside to the right, as in Figure 1.

Figure 3. Similarity solution models for [Fe XIV] surface brightness. The observations shown in Figure 2 have been shifted horizontally to best match the models. In (a) the shock velocity is 300 kms^{-1}, while in (b) it is 250 kms^{-1}. Higher velocities have the maximum [Fe XIV] surface brightness too close to the shock front while lower velocities require very large densities to match the observed surface brightness.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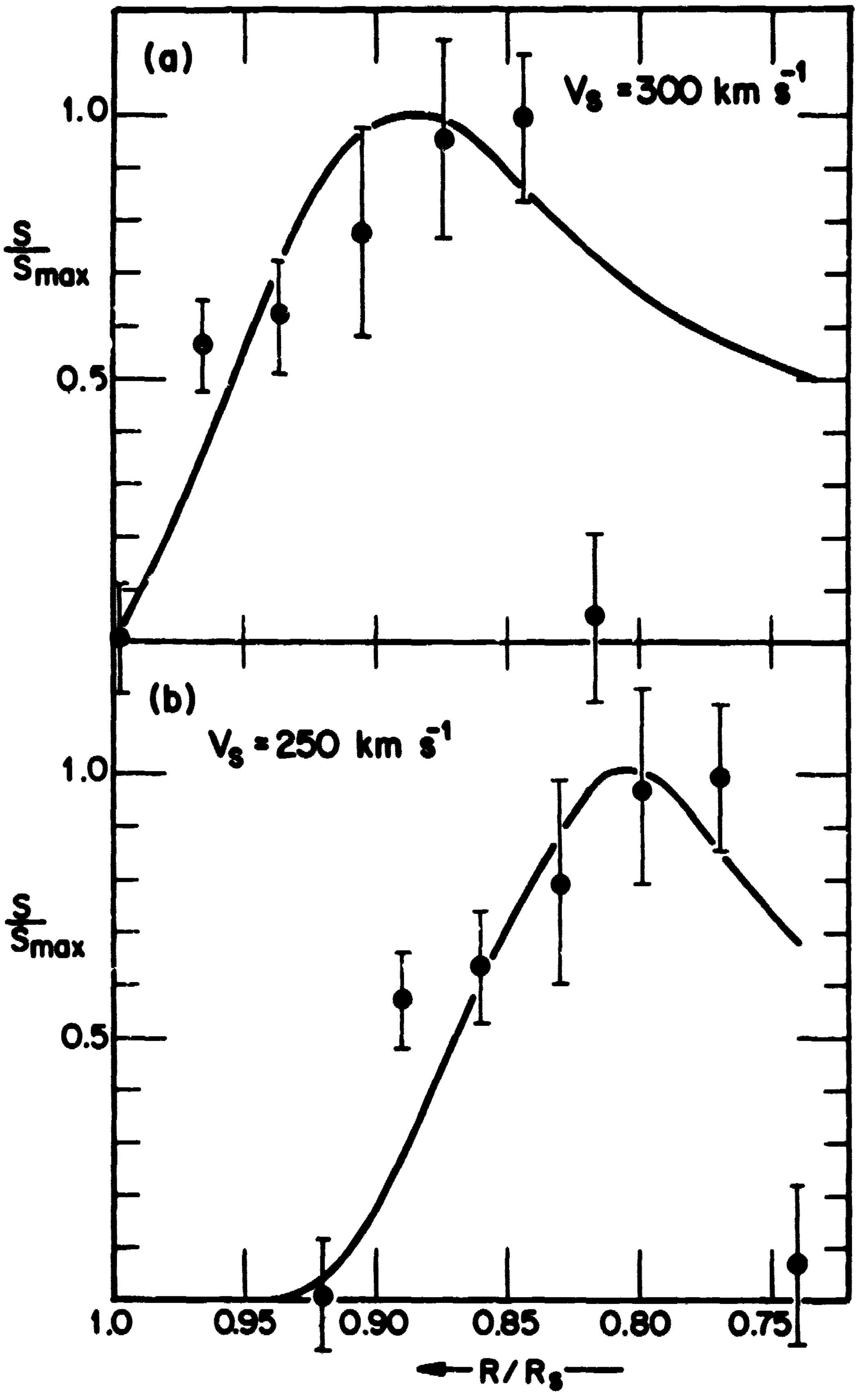
(a)
V_s = 300 km s^{-1}
1.0
0.5
$\frac{S}{S_{max}}$
(b)
V_s = 250 km s^{-1}
1.0
0.5
$\frac{S}{S_{max}}$
1.0
0.95
0.90
0.85
0.80
0.75
← R / R_s —