A THEORETICAL MODEL OF THE CYGNUS LOOP AND ITS X-RAY EMISSION

S.A.E.G. Falle and A.R. Garlick
Department of Applied Mathematics
University of Leeds,
Leeds, England

ABSTRACT

In this paper we present a theoretical model of the Cygnus Loop which, with only a small number of free parameters, accounts for most of the gross features of the observations. We believe that none of the models described in the literature can explain the observations in such a simple way.

OBSERVATIONS

Bright Filaments

The Cygnus Loop consists of a number of bright filaments arranged in an incomplete ring on the sky. There also are some filaments both outside and inside the ring. These filaments have been studied by a number of authors, in particular:--

a) Hubble (1937) looked at the proper motion of the filaments. He found a proper motion of 0.03" yr^{-1}. If this is combined with the radius of the remnant, then we find a 'Hubble' age $t_H=\theta/\dot{\theta}=150{,}000$ yr. Since the remnant has certainly been slowed down by interaction with interstellar material, the Hubble age represents an upper limit to the age.

b) Minkowski (1958) measured the radial velocity of some of the filaments. He found an expansion velocity ~116 km s^{-1}. If this is combined with a), then we find that the distance is 770 pc. This distance is somewhat uncertain since the radial velocity and proper motion do not refer to the same filaments. There is then the implicit assumption that the bright filaments constitute a roughly spherical expanding shell and that the proper motion measures the material velocity of the shell.

J. Danziger and P. Gorenstein (eds.), Supernova Remnants and their X-Ray Emission, 261–266.

c) Miller (1974) made photoelectric measurements of the line and continuum intensities in the filaments. He found an electron density of ~ 200 cm^{-3} at a temperature of ~ 12000 K. This means that the pressure is $\sim 6.6 \times 10^{-10}$ c.g.s. If the shock velocity is 116 km s^{-1}, then the ambient density must be $\sim 5 \times 10^{-24}$ gm cm^{-3}. He also deduced from the H_β intensity that the filaments are about 10 times deeper than their width, i.e. they are sheets seen edge on.

X-Ray Emission

a) Rappaport et al. (1974) found that although the X-ray emission correlates quite well with the optical, there is some X-ray emission outside the boundaries of the optical remnant.

The X-ray luminosity is 2×10^{36} erg s^{-1} in the band 0.15–1.5 keV. If the spectrum is fitted to a thermal spectrum, then the temperature is $2.9 \pm 1.5 \times 10^6$ K.

b) Rappaport et al. (1979) made scans of the X-ray intensity in the North-South and East-West directions. They found that there is less limb brightening in the South than in other parts of the shell. Note that the optical shell also appears less complete in the South.

Fast H_α Emission

Kirschner and Taylor (1976) have used the H_α emission to measure the radial velocities in the remnant. They found radial velocities in the range +200 to −300 km s^{-1}, and that the high ($S_\alpha \sim 10^{-4}$–10^{-5} erg cm^{-2} s^{-1} sr^{-1}) surface brightness features all have low velocities ($<+56$ km s^{-1}). The high velocity features have low surface brightness ($S_\alpha < 3 \times 10^{-6}$ erg cm^{-2} s^{-1} sr^{-1}).

Radio Observations

a) Moffat (1971) has observed the Cygnus Loop at 1420 MHz with the Cambridge half mile telescope. The radio and optical emission correlate quite well except in the South, where there is a considerable amount of radio emission outside the boundary of the optical remnant. The spectrum is non-thermal with an index of ~ 0.45. Polarisation measurements show that the magnetic field is generally aligned with the optical filaments. This suggests that the radio emission is due to compression of the interstellar medium (van der Laan 1962).

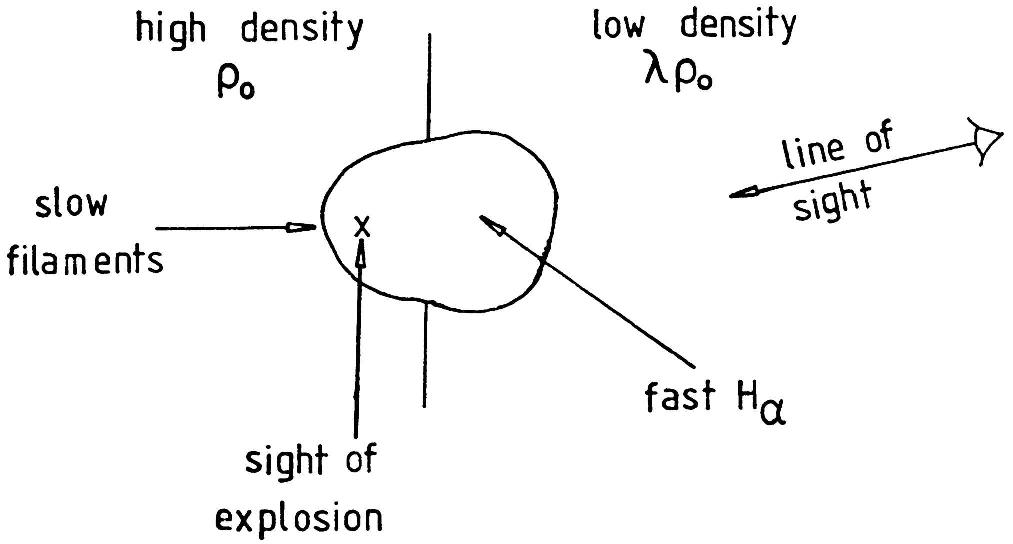
b) De Noyer (1975) made 21 cm observations of the remnant with the NRAO telescope with a velocity resolution of 3.3 km s^{-1}. She was looking for the expanding HI shell that should exist if the remnant is in the radiative phase. She found that the surface density σ of such a shell must satisfy

$$\sigma \lesssim 2.7 \times 10^{18} \Delta V \text{ gm cm}^{-2}$$

where ΔV is the velocity dispersion in the shell (in km s^{-1}). If the remnant is in the radiative phase, we would expect $\sigma \sim 2 \times 10^{19}$ gm cm^{-2}. However, if the ambient density is slightly non-uniform, then there would not be a single shell, but a number of shells with velocities differing by ~10 km s^{-1}. The effective velocity dispersion would then be 10 km s^{-1}, and these observations would not preclude the remnant being in the radiative phase.

THEORETICAL MODEL

We shall now show that the observations just described, as well as other features of the remnant, can be explained if the interstellar medium has a steep density gradient. For simplicity we will consider a density discontinuity, but the results would not be greatly altered if the density changes more gradually. All that is required is that the density scale height be somewhat less than the present size of the remnant. The picture is as shown in figure 1.



a) 'Breakout' leads to high velocities.

b) The fast H_α emission comes from originally dense gas which has been accelerated.

c) The X-ray emission from the shocked low density gas extends beyond the optical remnant.

d) The slow filaments and the soft X-rays are approximately as for a spherical remnant in the dense gas.

e) The orientation explains the incomplete optical shell and the X-ray limb brightening.

CALCULATION OF THE THEORETICAL PARAMETERS

We need to determine:--

1) The energy of the explosion	E_0
2) High ambient density	ρ_0
3) The density ratio	λ
4) The distance of the explosion from the contact discontinuity	d
5) The age of the remnant	t

From the observations we have:--

1) Radius	$R \sim 18$ pc
2) Slow filament velocity	$v_s \sim 100$ km s^{-1}
3) Fast H_α velocity	$v_f \sim 300$ km s^{-1}
4) Pressure in the slow filaments	$p_s \sim 6.6 \times 10^{-10}$ c.g.s.
5) Fast H_α surface brightness	$S_\alpha \sim 3 \times 10^{-6}$ erg cm^{-2} sr^{-1} s^{-1}
6) X-ray luminosity (0.15-1.5 keV)	$L_x \sim 2 \times 10^{36}$ erg s^{-1}
7) X-ray temperature	$T_x \sim 2.9 \pm 1.5 \times 10^6$ K

We also know that:--

8) The radius of the remnant in the dense gas is about the same as that in the diffuse gas, since if it were smaller there would be no X-ray emission outside the optical remnant, while if it were much larger the X-ray emission would extend considerably beyond the boundaries of the optical remnant.

9) The X-ray emission from the diffuse gas is about the same as from the dense gas. This is because the X-ray intensity just outside the optical remnant, which comes from the diffuse gas, is about the same as that inside.

To determine E_0, ρ_0, λ, d and t we proceed as follows. From the pressure p_s in the bright filaments we find $\rho_0 = 5 \times 10^{-24}$ gm cm^{-3}. We then do some adiabatic axisymmetric numerical calculations with different values of λ, which is the only dimensionless parameter in such a calculation. Let t_b be the time at which the shock reaches the contact discontinuity, i.e. the breakout time. From the fact that the remnant must be the same size on both sides of the discontinuity, we find that $t/t_b \sim 9$ and from v_f/v_s we get $\lambda \sim 0.05$. From the observed radius we then get $d \sim 8$ pc.

It is not a bad approximation to use an adiabatic calculation for this as we shall find that cooling does not become important until after breakout. Cooling does then not have much of an effect on the dynamics of the gas which has broken out.

Up to the times which we consider, it can be shown that the behaviour of the remnant in the dense gas is the same as for a spherical remnant. We therefore carry out a spherically symmetric numerical calculation (Falle 1981) with cooling. This is done with different values of E_0 and with $\rho_0=5\times10^{-24}$ gm cm^{-2}. We then find the time at which the material velocity is equal to v_s. Then choose E_0 such that the radius and X-ray luminosity match the observed values. Note that since we have only one free parameter E_0 and two observables R and L_x, the fact that these two values can be matched provides a test of the validity of the model.

Finally we calculate the H_α surface brightness of the broken out material which is cooling now. It is this material which in our model produces the faint fast H_α emission.

The results of all this are:—

Parameter	Theoretical	Observed
E_0	7×10^{50} erg	
ρ_0	5×10^{-24} gm cm^{-3}	
λ	0.05	
t	7×10^{4} yr	
t_b	7.4×10^{3} yr	
t_c (cooling time)	1.4×10^{4} yr	
v_s	100 km s^{-1}	100 km s^{-1}
v_f	300 km s^{-1}	300 km s^{-1}
L_x	2×10^{36} erg s^{-1}	2×10^{36} erg s^{-1}
p_s	6.6×10^{-10} c.g.s.	6.6×10^{-10} c.g.s.
R	20 pc	18 pc
T_x	Dense gas 10^6 K	
	Diffuse gas 2.4×10^6 K	$2.9\pm1.5\times10^6$ K
S_α	$<5\times10^{-6}$ c.g.s.	$<3\times10^{-6}$ c.g.s.

It can be seen that the observed and theoretical values agree very well. Furthermore there are more observed values than there are free parameters in the theoretical model, so that this agreement is a genuine test of the model. This is in contrast to other models which either have a large number of free parameters, or fail to account for all of the observations.

REFERENCES

De Noyer, L.K. 1975, Astrophys. J., 196, 479.
Falle, S.A.E.G. 1981, Mon. Not. R. astr. Soc., 195, 1011.
Hubble, E.P. 1937, Carnegie Yrb., No. 36, p. 189.
Kirschner, R.P. and Taylor, K. 1976, Astrophys. J., 208, L83.
Laan, H. van der, 1962, Mon. Not. R. astr. Soc., 124, 127.
Miller, J.S. 1974, Astrophys. J., 189, 239.
Minkowski, R. 1958, Rev. Mod. Phys., 30, 1048.
Moffat, P.H. 1971, Mon. Not. R. astr. Soc., 153, 401.

Rappaport, S., Doxsey, R., Solinger, A., and Borken, R. 1974, Astrophys. J., 194, 329.
Rappaport, S., Petre, R., Kayat, M.A., Evans, K.D., Smith, G.C., and Levine, A. 1979, Astrophys. J., 227, 285.

DISCUSSION

DICKEL: Geometrically just where is the discontinuity?

FALLE: Nearly perpendicular to the line of sight.

MCKEE: The gas producing the blueshifted emission lines was shocked at a time of less than 10^4 yr and thus reached X-ray emitting temperatures. Has there been time for this gas to cool off and produce the observed optical emission?

FALLE: Yes. We used Kahn's approximation to estimate the rate at which material was cooling. This is how we calculated the fast H_α surface brightness.