Crab Nebula. This is not surprising in view of the large difference in age and volume between the objects. The large x-ray flux might be responsible for the excitation of the optical line emission observed from the filaments of the Cygnus Loop. However, in the hot plasma hypothesis one encounters the difficulty of explaining the lack of consistency between the high temperature observed in the x-ray region and the apparent low expansion velocity of the filaments.

We now know of two classes of x-ray sources among the supernova remnants—the remnants of events that took place less than 10^3 years ago, and those more than 10^4 years old. Members of the first class, for example Crab Nebula, Tycho's Supernova, and Cas A, are visible at energies above 2 kev while members of the second class have been seen only below 1 kev. The Cygnus Loop belongs to the second class and a recent report by Palmieri *et al.* (*10*) adds Vel X and Pup A to this class. The x-ray emission mechanism is known for only one member of the first class, the Crab Nebula, and it is synchrotron radiation. Our results suggest that another mechanism, thermal radiation from a hot plasma, is responsible for the emission from the second class.

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Soft X-rays from the Cygnus Loop: Interpretation

Abstract. *Two possible interpretations of the recent soft x-ray observation of the Cygnus Loop are discussed. A synchrotron model requires a magnetic field less than 10^{-6} gauss and electron energies in excess of 10^{14} electron volts. These electrons must either have been reaccelerated or continuously injected into the source for about 50,000 years. The observations are also consistent with the radiation from a hot plasma having the cosmic abundances of the elements. A likely origin for the hot plasma is a blast wave produced by the explosion of a supernova in the interstellar medium. Fitting such a model to the observations implies a kinetic energy release in the explosion of 6×10^{50} ergs, for an assumed distance of 770 parsec.*

The soft x-ray observations of the Cygnus Loop (*1*) provide information concerning the structure of the source, its intensity, and its spectrum. In summary, the observations show that (i) the source has a shell-like structure with an outer diameter of about 3 deg; (ii) the flux from the Cygnus Loop in the 10- to 80-Å region is $\approx 2 \times 10^{-8}$ erg/cm^2-sec; and (iii) the measurements of the spectrum of the source can, at this time, best be fit by an exponential emission function with an electron temperature $T \sim 4 \times 10^6$ °K plus an emission line around 20 Å. The intensity of the line is roughly equal to the integrated continuum emission in the 15 to 20 Å range. The feature around 20 Å could also be produced by a power law spectrum characterized by a large change in the spectral index between 20 Å and 15 Å, so that the results can be interpreted in terms of either a synchrotron or a hot plasma model.

In the synchrotron model the shell structure could be due to the enhanced radiation of the high energy electrons as they encounter regions of high magnetic field near the boundary of the nebula, as in models for the radio emission. Extrapolation of the observed radio spectrum (*2*) down to 20 Å yields a flux of the right order of magnitude, so a unified synchrotron spectrum extending from radio to x-ray wavelengths is not precluded by the observations. A sharp break in the spectrum between 20 Å and 15 Å would result if there were a sharp change in the electron spectrum at the appropriate energy. This change could be intrinsic to the mechanism for producing the high energy electrons, or it could be due to synchrotron losses. The radiative half-life for an electron that produces synchrotron radiation of frequency ν in a perpendicular magnetic field $B_\perp$ (in gauss) is

$$t_{1/2} \approx 6 \times 10^{11}/B_\perp^{3/2}\nu^{1/2} \text{ seconds}$$

A break in the spectrum will appear near the frequency for which $t_{1/2} = t_{\mathrm{neb}}$, the age of the source. For $B_\perp \approx 10^{-6}$ gauss and $\nu = 1.5 \times 10^{17}$ hz (the frequency at 20 Å), $t_{1/2} \approx 50{,}000$ years, a little less than, but in rough agreement with, other estimates of the age of the Cygnus Loop (*2*). For magnetic fields of this strength the energy of the electrons producing the soft x-radiation is $\sim 10^{14}$ ev; and the total energy of all the electrons in the source is $\approx 10^{48}$ ergs, somewhat greater than the energy in the magnetic field. In order for the spectrum to be a single power law from radio down to x-ray wavelengths, continuous injection or reacceleration of the high energy electrons must have taken place for about 50,000 years or until the magnetic field of the expanding nebula dropped to a value of about 10^{-6} gauss; otherwise synchrotron losses would have produced a break at much lower frequencies. In summary, the parameters of a synchrotron model are extreme but perhaps not so extreme as to exclude it.

Of course, if we accept the existence of an emission line in the spectrum, this rules out any x-ray production mechanism other than radiation from a hot plasma. Nonthermal processes, such as the characteristic x-ray line emission that follows K-shell ionizations by fast protons (*3*) or the decay of excited states after charge-exchange processes between hydrogen atoms and heavy cosmic ray particles (*4*), could in principle result in x-ray line emission; but their low efficiency ($\lesssim 10^{-5}$) would require prohibitively large nonthermal particle fluxes ($\gtrsim 10^{41}$ erg/sec).

On the other hand, the spectral observations can be explained quite readily in terms of radiation from a hot plasma. Figure 1 shows the spectrum of a hot, optically thin plasma—computed on the assumption that the plasma has a temperature of 4×10^6 °K, is optically thin to its own radiation, and has the abundances given by Brown and Gould (*5*). The ionization equilibrium calculations of Jordan (*6*) which are appropriate to a low density plasma were used. A resolution of 0.5 Å was assumed, and the following processes were included: line emission following radiative decay of excited states produced by electron collisions and continuum emission produced by bremsstrahlung, recombination, and two photon decay of metastable states in hydrogenic and heliumlike ions. The prominent lines are labeled according to the ion and the transition.

An important feature of this spectrum is the strong Lyman-α line of O VIII at 18.96 Å. It should be noted that the O VII $1s^2$-$1s2p$ lines around 21.6 Å are also quite strong, and at lower temperatures, around 2×10^6 °K, these lines dominate. The experiment of Gorenstein *et al.* did not have sufficient resolution to discriminate between the O VII and O VIII lines. In addition, there are other strong lines in the 10- to 15-Å region, notably Ne IX, which might produce enough flux in this region to introduce a significant error into the method of determining the temperature by means of an exponential plus a single line. Thus the temperature might well be lower by about 2×10^6 °K. Observation of [Fe X]λ6374 emission from the Cygnus Loop (*7*) provides evidence for a lower temperature, around 1 or 2×10^6 °K. What is the origin of the hot plasma? Production by a shock wave is the most attractive hypothesis. The possibility that supernova outbursts can produce shock waves in the interstellar medium has been recognized for many years (*8*), and x-ray emission from the hot plasma behind shock waves produced by supernovas has been discussed by several authors (*9, 10, 11*). Shock velocities V_s of the order of 400 to 600 km/sec are required in order to produce a temperature of 2 to 4×10^6 °K. This is about a factor 4 or 5 greater than the expansion velocity V_f of the filamentary system of the Cygnus Loop, as determined by Minkowski (*12*) on the basis of Doppler shift measurements, but a value of $V_s/V_f \approx 4/3$ would be expected on the basis of the theory of shock waves. There are essentially two possibilities. (i) The discrepancy is real, and the filaments actually are moving a great deal slower than the shock front; or (ii) the discrepancy is only apparent, and the expansion is proceeding (or appears to proceed because of limb brightening effects) at almost a right angle to the line of sight so the Doppler shift measurements give us at most an estimate of only a small component ($\sim 1/5$) of the total velocity of the filaments.

The first alternative requires that the motion of the filaments be unrelated to the motion of the shock front. The existence of slowly moving filaments in a rapidly expanding medium is not unique to the Cygnus Loop; similar features exist in Cas A and Tycho, for example. The similarity in size and structure of the Cygnus Loop x-ray source and the optical filamentary system further requires either that we are observing the Cygnus Loop during a special period of its existence, or that the filaments disappear in a time which is short compared to the expansion time of the source. A recent study of the optical filaments in Cas A has shown that most of them have a lifetime of the order of 10 years or less (*13*). In the case of the Cygnus Loop an upper limit of a few thousand years on the age of the filaments is required. If we adopt alternative (i), the distance (770 parsec) and radius (20 parsec) remain as determined by Minkowski (*12*); however, the age becomes only 12,000 to 20,000 years, if it is based on the shock velocity. At this distance the soft x-ray luminosity is $\approx 10^{36}$ erg/sec. Theoretical studies (*10, 11*) of the flow behind the shock front show that the power radiated in a photon energy band $\Delta\varepsilon$ by the shock-heated plasma may be approximated by

$$L(\Delta\varepsilon) \approx 3 \times 10^{56}\, n_1^2\, R_s^3\, P(\Delta\varepsilon, T) \quad \text{erg/sec} \qquad (1)$$

where n_1 is the density of the gas in front of the shock, R_s is the radius of the shock in parsecs (1 parsec = 3.26 light years), and $P(\Delta\varepsilon, T)$ is a function which describes the emissivity of a low density plasma with a temperature T. For $T = 4 \times 10^6$ °K, and $\Delta\varepsilon =$ 0.2 to 1.0 kev, the emissivity $P(\Delta\varepsilon, T) = 2 \times 10^{23}$ erg/cm^3-sec (*14*). With this value and the observed radius of 20 parsec for the Cygnus Loop, Eq. 1 shows that an interstellar density $n_1 = 0.16$ is required in order to explain a soft x-ray luminosity of 10^{36} erg/sec.

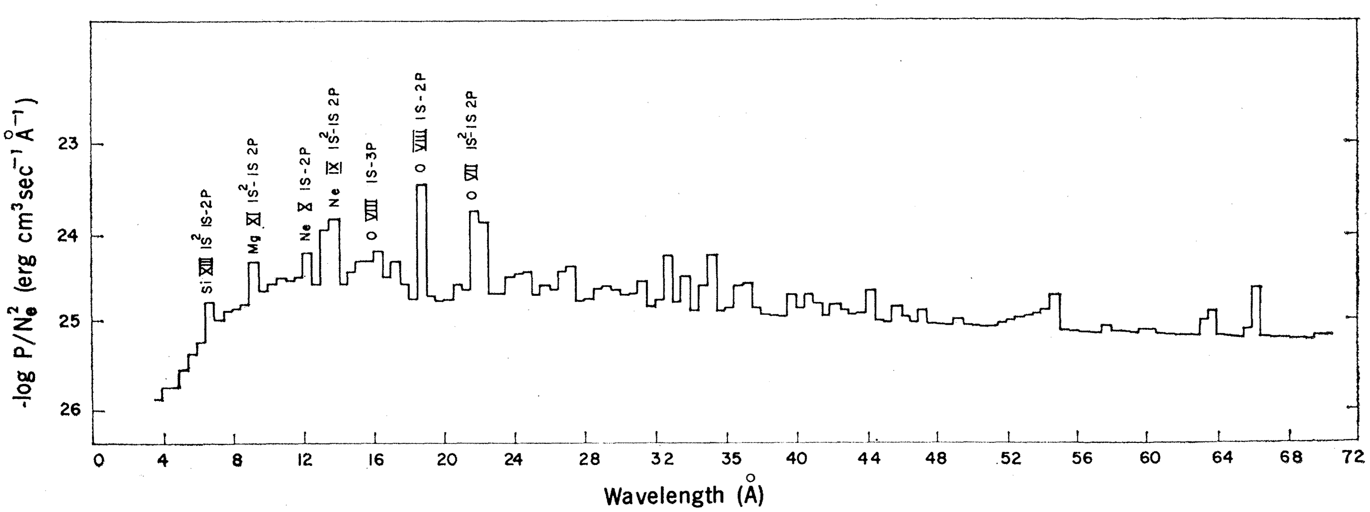

Fig. 1. X-ray spectrum of a hot, optically thin plasma which has the cosmic elemental abundances. The resolution is 0.5 Å, and the electron temperature is assumed to be equal to 4×10^6 °K. The processes of line radiation, radiative recombination, two photon emission, and bremsstrahlung have been included. The prominent lines are labeled according to ion and transition. P is the emissivity and N_e is the electron density.

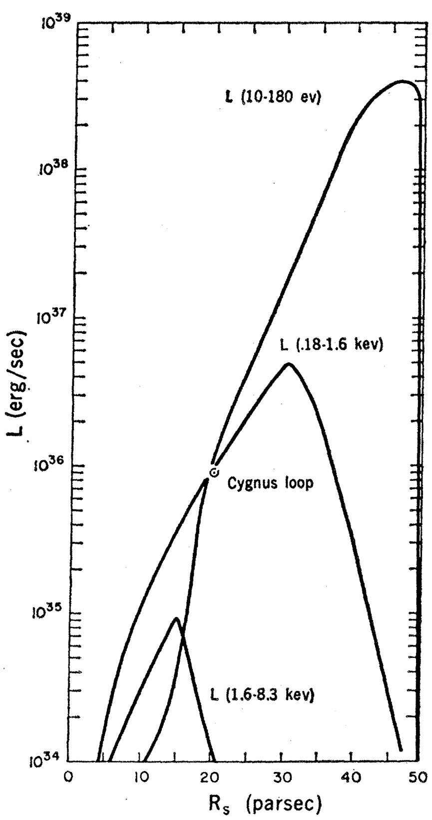

Fig. 2. Luminosity of supernova-produced blast waves in three different energy intervals as a function of the radius of the blast wave. The curves have been normalized to give the correct 0.18 to 1.6 kev flux for the Cygnus Loop at a distance of 770 parsec.

This fixes the energy, E, driving the shock at about 6×10^{50} ergs.

As the shock wave expands, it slows down and the temperature after the shock is consequently lower. Thus the emission is shifted to longer wavelengths and increases with time, because of the larger mass of matter in the swept-up shell. This process continues until radiative losses become important, after which time the emission fades out rapidly. Radiative losses become important for the Cygnus Loop at t_c (the cooling age) $\sim 130{,}000$ years, at which time its radius will be ≈ 50 parsec and the temperature after shock will be $\approx 2 \times 10^5$ °K. During these last phases the shock will have a total luminosity $\sim 4 \times 10^{38}$ erg/sec and will radiate most of its energy in the 10- to 30-ev region in the form of resonance lines of lithium-, beryllium-, and boron-like ions of oxygen and neon. This evolutionary behavior is illustrated in Fig. 2, where the luminosity in different energy bands is plotted versus the radius of the shock wave (the radius R_s is proportional to $t_{neb}{}^{2/5}$). This figure shows that supernova remnants having radii in the range 20 to 35 parsec will in general be strong sources of soft x-rays.

The second alternative, that the expansion is anisotropic, could arise quite naturally if the shock wave formed only in a direction perpendicular to the magnetic field, and if the direction of the magnetic field in the vicinity of the Cygnus Loop is parallel to the line of sight, to within 10 deg. Alternatively, the ejection of matter in the initial explosion could have been anisotropic. In this case the motion of the filaments can be identified with the motion of matter behind the shock, so that the total velocity of the filaments $V_f \approx 0.75\ V_s \approx 300$ to 400 km/sec. The proper motion measurements then imply a distance of about 2000 to 3000 parsec. At this distance the radius of the source is about 50 to 75 parsec; its soft x-ray luminosity is 1 to 2×10^{37} erg/sec; its age is somewhere between about 70,000 and 140,000 years, and the energy driving the shock is $\gtrsim 6 \times 10^{52}$ ergs, depending on the temperature and the degree of anisotropy of the explosion. The rather large value of the energy would argue against a distance as large as 3000 parsec. Unfortunately, for an object as far above the galactic plane as the Cygnus Loop ($\cong 110$ parsec), the data on soft x-ray absorption by the interstellar medium provide little information concerning the distance.

Finally, let us consider the consequences of assuming that the type of event that produced the Cygnus Loop occurs with a frequency $f = 10^{-2}$ per year per galaxy. Then the integrated spectral luminosity of the galaxy due to these sources is

$$\bar{L}_{\mathrm{gal,\ sn}}(\varepsilon) = f \int_{t=0}^{t_c} L(\varepsilon, t)\,dt$$

$$= f\,L(\varepsilon) \text{ erg/sec-kev}$$

Computation of this integral for $E = 6 \times 10^{50}$ ergs and $n_1 = 0.16$ yields $\bar{L}_{\mathrm{gal,\ sn}}(\Delta\varepsilon) \approx 3 \times 10^{41}$ erg/sec with $\Delta\varepsilon \approx 10$ to 30 ev (ultraviolet), and $\bar{L}_{\mathrm{gal,\ sn}}(\Delta\varepsilon) \approx 4 \times 10^{38}$ erg/sec for $\Delta\varepsilon \approx 150$ to 1000 ev (soft x-ray). For $E = 6 \times 10^{52}$ ergs and $n_1 = 0.24$ the luminosities are a factor 70 higher. Most of the energy of the remnant is emitted in the 10- to 30-ev range, not in the oxygen Lyman-α lines as suggested by Shklovsky (*9*) and Heiles (*10*).

Even for $E = 6 \times 10^{50}$ ergs the rate at which energy is deposited in the interstellar medium is sufficiently large ($\sim 3 \times 10^{41}$ erg/sec) that ultraviolet and x-ray emission from supernova-produced blast waves must be considered as an important heat source in the interstellar medium (*15*). In fact, we can probably rule out the possibility that the average kinetic energy produced by a supernova explosion is as great as 6×10^{52} ergs, since in that case the average energy input into the interstellar medium ($\sim 2 \times 10^{43}$ erg/sec) would appear to be too large.

For an average $E = 6 \times 10^{50}$ ergs and a frequency of 1 per 100 years per galaxy, the contribution of these events to the soft x-ray (0.15 to 1.0 kev) background is $\sim 7 \times 10^{-10}$ erg/cm^2-sec sterad, about a factor of 30 less than the observed value (*16*). This estimate takes no account of possible evolutionary effects, such as a high supernova frequency during the early phases of a galaxy's existence. Unless such effects are important, it is unlikely that sources like the Cygnus Loop make a large contribution to the soft x-ray background.

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