Reports

X-ray Structure of the Cygnus Loop

Abstract. *X-ray emission from the Cygnus Loop was observed in the energy region around 0.2 to 1 kiloelectronvolt with a collector that focused x-rays along one dimension while scanning across the nebula. The total integrated intensity is* 1.3×10^{-8} *erg per square centimeter per second. The one-dimensional x-ray structure has the same angular size—about 3 degrees—as the outermost boundaries of the optical filaments. There is no increase in x-ray emission at the center of the nebula nor at the strong feature that is seen in certain radio maps. The x-ray spectrum is consistent with thermal radiation from a hot plasma at a temperature of about* 4×10^6 *°K with evidence for a line at 19 angstroms corresponding to the* 2p→1s *transition of O VIII.*

X-ray emission from the supernova remnant known as the Cygnus Loop or Veil Nebula was observed in the energy range 0.2 to 1 kev from an attitude-controlled Aerobee 170 sounding rocket that was launched at 4:55 U.T. on 26 June 1970 from the White Sands Missile Range. Grader, Hill, and Stoering (*1*) have reported intense x-ray emission in this energy range from an extended object which they identified with the Cygnus Loop. Also this object is very likely coincident with the x-ray source Vul XR-1 which had been reported previously with an imprecise location (*2*).

The purposes of this observation were to (i) obtain a precise location that would confirm the identification by Grader *et al.* of the extended x-ray source with the Cygnus Loop, (ii) obtain a high resolution map of the x-ray emission that could be correlated with the optical and radio pictures of the Cygnus Loop, (iii) distinguish between a thermal and nonthermal emission mechanism on the basis of a spectral analysis of the x-ray data.

We used a rather unique instrument system, which focused x-rays by means of grazing incidence reflection, in this observation. For x-ray wavelengths exceeding 10 Å, the potential advantages of focusing compared to conventional systems are better angular resolution and an improved ratio of signal to noise because the focused image is considerably smaller than the collecting area. Hence, the detector can be small and less influenced by cosmic ray effects. Also the reflecting surfaces effectively block the direct path of soft charged particles that are sporadically present in the space environment. These particles would otherwise penetrate the thin entrance window of the detector and add to the background. This particular instrument consists of a collector that focuses radiation in one dimension upon a multielement x-ray detector in the focal plane. The collector has eight nested reflecting plates whose dimensions are 20 by 40 cm and is symmetric about the central plane. Each plate is curved slightly to approximate a parabola in one dimension and focuses to a common line. The overall field of view of the instrument is 2 deg along the direction of focusing and 9 deg along the perpendicular direction.

The eight reflecting surfaces are commercial 1-mm-thick float glass overcoated with an evaporated layer of 1500 Å of chromium for improved x-ray reflectivity at short wavelengths and are reinforced by a steel backing. The focal plane detector is a pair of four-wire proportional counters with a polypropylene entrance window of 1.3 μm. The wires were spaced at a distance equivalent to an angular separation of 0.5 deg, which determines the angular resolution of the system. A regulated supply system of pure propane gas compensated for natural losses through the thin polypropylene windows by maintaining the pressure at 50 cm-Hg. The energy resolution of the detectors gave a full width at half maximum in the pulse amplitude distribution of 100 percent of the peak amplitude for photon energies (wavelengths) of 0.28 kev (44 Å) and about 40 percent at 1.25 kev (10 Å). The entire system is sensitive in the wavelength bands 80 to 44 Å (0.16 to 0.28 kev) and 20 to 10 Å (0.6 to 1.2 kev). Photography of the star field at intervals of 1 second provided the aspect data. More instrumentation details are described elsewhere (*3*).

This observation took place during the later phases of the rocket flight prior to reentering the earth's atmosphere. X-ray data from other regions of the sky will be reported separately. Approximately 1500 net counts were obtained during a single scan across the Cygnus Loop that took place at a rate of 0.25 deg/sec. Figure 1 shows the angular response of four independent detectors to the Cygnus Loop plus, for purposes of comparison, the response to well-collimated radiation in the laboratory. Count data from the four detectors can be combined with the aspect information and represented in celestial coordinates. The result (Fig. 2) is a one-dimensional x-ray map of the Cygnus Loop superimposed upon an optical photograph of the Loop.

Several conclusions follow from a comparison of these maps. (i) The size and structure of the x-ray emission is consistent with that of the shell-like region bounding the optical filaments; the diameter of the x-ray region is about 2.8 deg, like that of the outermost boundaries of the filaments, and there is no increase in x-ray emission at the center of the nebula. (ii) To within the resolution of the instrument, 0.5 deg, the amount of x-ray emission declines rather sharply at the outer boundaries of the optical filaments. (iii) The strong central feature that appears in a radio contour map (*4*) does not coincide with a strong maximum in the x-ray emission.

A spectral analysis was made of the pulse amplitude distribution of the counts from the Cygnus Loop. The usual procedure was followed; an x-ray emission spectrum containing undetermined parameters is multiplied by all the known efficiencies and is convolved with a resolution function that simulates the pulse amplitude distribution response of the proportional counter to monoenergetic photons at any energy (*5*). For each set of parameter values the extent of agreement between the computed and observed pulse amplitude spectra is quantitatively measured on the basis of a minimum chi-square test. Grazing incidence telescopes require a correction for an energy-dependent x-ray reflection efficiency. A theoretical efficiency function was computed for this particular instrument from the reflection properties of chromium as measured by Ershov, Brytov, and Lukirskii (*6*). The theoretical telescope efficiency was confirmed at 1.25 kev by laboratory measurements.

At the estimated distance to the Cygnus Loop, 770 parsec (*7*), the opacity of the galaxy becomes significant for x-ray energies, ε, less than 0.3 kev. In our analysis a set of x-ray attenuation coefficients for the interstellar medium recently computed by Brown and Gould (*8*) for revised helium and neon abundances were used to calculate Tr (ε, N_H), the interstellar transmission. The value of N_H, the number of hydrogen atoms along the line of sight, was left as an undetermined parameter. The large volume of the Cygnus Loop precludes any internal absorption.

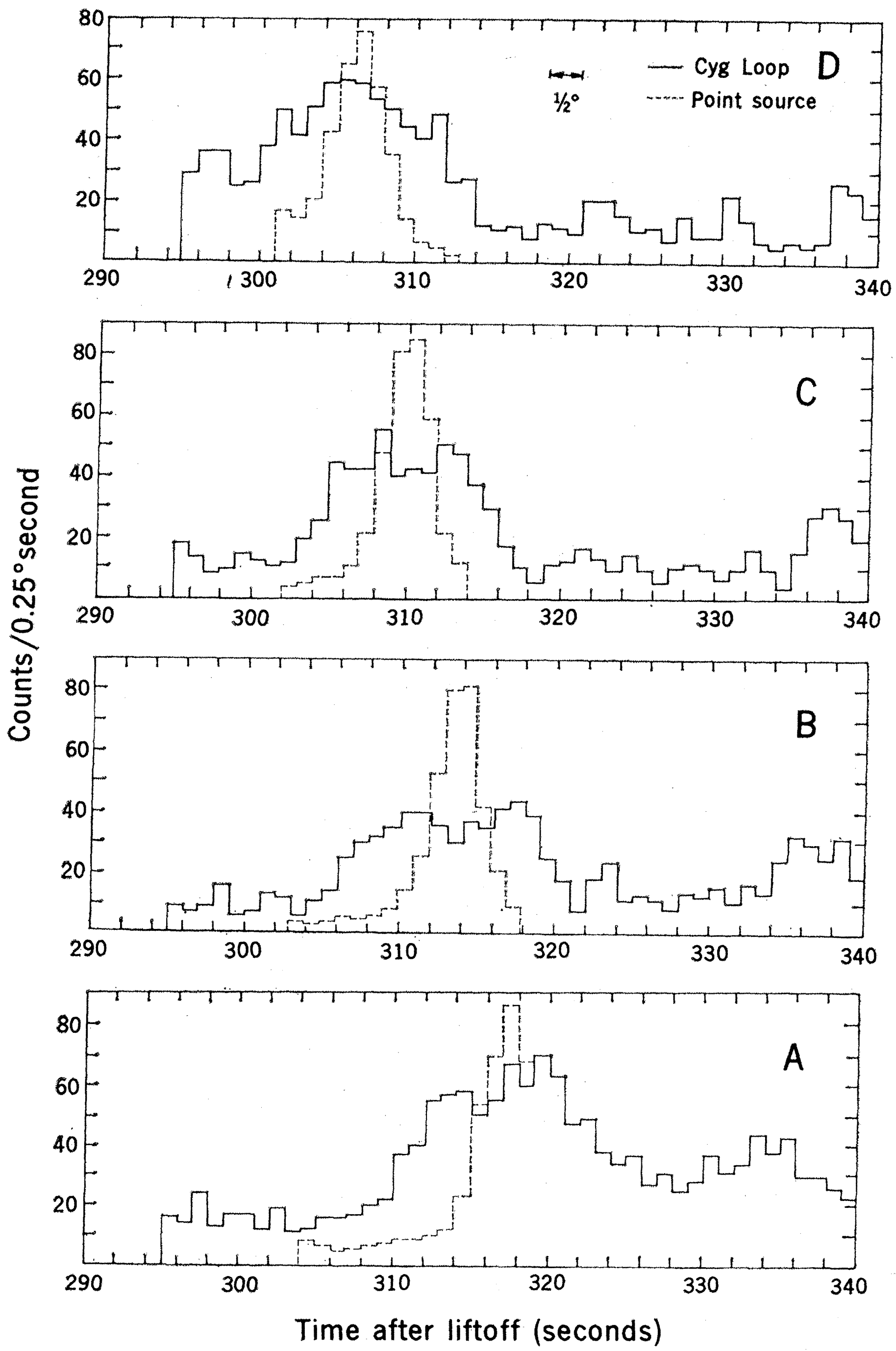


Fig. 1. Solid lines are the response of four independent proportional counter elements in the focal plane during a scan of 0.25 deg/sec across the Cygnus Loop. Dotted lines represent instrument response to a point source at 80 m.

Two classes of spectral functions multiplied by interstellar transmission were considered:

$$dN/d\varepsilon = A \,\mathrm{Tr}\,(\varepsilon, N_H)\varepsilon^{-\alpha} \qquad (1)$$

$$dN/d\varepsilon = A \,\mathrm{Tr}\,(\varepsilon, N_H) \times \{\exp(-\varepsilon/kT)/\varepsilon + B\,\delta\,(\varepsilon - 0.65 \text{ kev})\} \qquad (2)$$

The quantities α, T, N_H, B, and A are the undetermined fitting parameters. The two expressions represent alternative physical processes resulting in x-ray emission.

Equation 1 represents the type of spectrum that could be produced by synchrotron radiation, for example, the Crab Nebula, where α is the spectral index. Equation 2 approximates the thermal emission spectrum that one expects from a hot plasma, with a temperature T, that contains a cosmic elemental abundance. The actual spectrum would consist of a continuum plus a number of lines and recombination edges. A line of 0.65 kev corresponding to the $2p \rightarrow 1s$ transition of O VIII would be a prominent feature of the thermal x-ray emission from the boundaries of a shock wave that has been produced as a result of a supernova explosion expanding into the interstellar medium (*9*). We represent this feature by a delta function of amplitude B, in Eq. 2.

The results of the analysis show that Eq. 1 is inconsistent with our data for all possible values of α. However, one can probably not exclude more complex expressions that might arise from synchrotron radiation as, for example, a power law spectrum that is characterized by a large change in the spectral index between 20 and 15 Å. Equation 2 did fit the data with an acceptable value of the chi-square and a finite strength of the line at 0.65 kev. Because Eq. 2 is only an approximation to the actual spectrum of radiation from a hot plasma, the temperature found as a result of fitting this expression to our data is not necessarily the true temperature of the plasma. The observed and computed pulse height distributions are shown in Fig. 3. The parameters associated with the best (minimum chi-square) fit are:

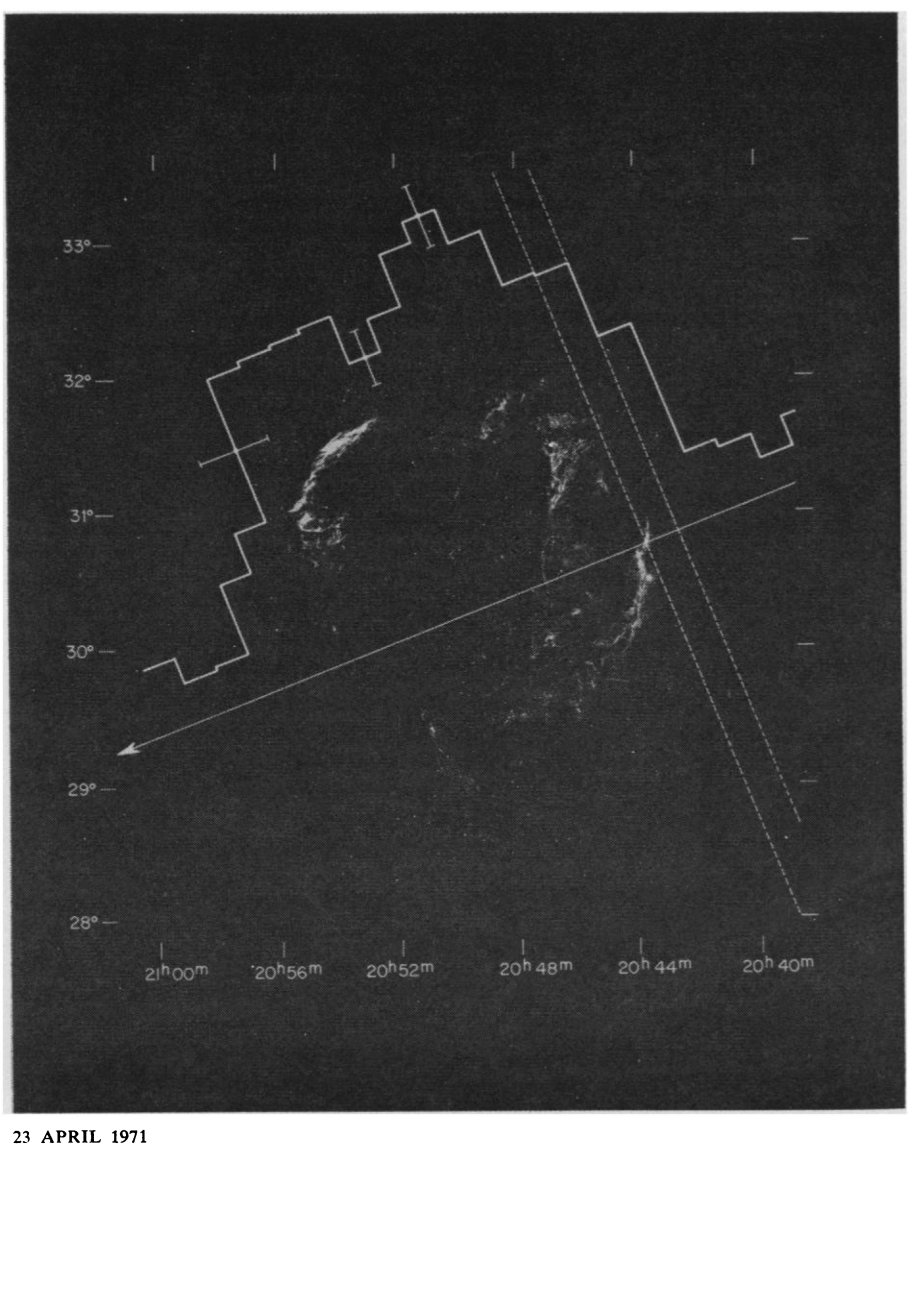
$$T = 4.3 \times 10^6 \text{ °K}$$

$$N_H = 2.6 \times 10^{20} \text{ H atom/cm}^2$$

Total integrated intensity =
1.3×10^{-8} erg/cm²-sec $\quad 0.2 < \varepsilon < 1$ kev

The most outstanding result of the analysis is that about one third of the energy for which $\varepsilon > 0.2$ kev from the Cygnus Loop is contained in a line at 0.65 kev. If true, it is rather firm evidence that the source of the x-ray emission is a hot plasma and that high temperature exists in old supernova remnants. Hence, it is important to examine this result rather carefully. Inspection of the raw pulse height data from the Cygnus Loop shows that there are a large number of counts between 0.55 and 0.75 kev. This results in the line at 0.65 kev in the analysis. This feature is not questionable on the basis of its statistical significance, and if spurious it originates in systematic errors. The most important possible systematic errors are incorrect reflection efficiency of the collector and an incorrect energy calibration of the proportional counters. Both these effects would be confined to the region around 0.65 kev since the other parameters we determine for the Cygnus Loop spectrum are in agreement with (*1*). As for the first effect, it is true that the x-ray reflection efficiency of the chromium collector undergoes large changes in the vicinity of the chromium L edges. However, actual experimental values of reflectivity including edge effects as measured by Ershov *et al.* (*6*) were used in the calculation of the collector efficiency function. Additional measurements at several wavelengths on chromium plates similar to the ones used in the collector confirmed the applicability of the theoretical reflectivity to our chromium surfaces. To simulate the effect of a line the value we used for the collector efficiency would have to be low by about a factor of 2 at 0.65 kev, and we feel that this large an error is unlikely. The other possible systematic error is an incorrect energy calibration of the proportional counter pulse amplitude response. The calibration is based on an irradiation of the counters with characteristic x-rays of 0.185, 0.282, 0.68, and 1.25 kev several days before flight; one of these calibration points is very close in energy to the oxygen line. There are several indications in the flight data that the energy calibration is correct. A large increase in counting efficiency occurs below 0.28 kev due to the K edge of carbon in the detector window, and in general the pulse height distribution reflects this feature. Errors in energy calibration would also distort other data as well as the Cygnus Loop, but for both background data and another source seen in this experiment, Cyg X-1, there are no indications of anomalies at 0.65 kev, the energy of the line.

If we exclude the possibility that the spectral function is undergoing rapid changes in the wavelength interval of the observation, then the most likely form of the x-ray emission is radiation from a high temperature plasma. Hence the process responsible for the x-rays from the Cygnus Loop appears to be quite distinct from that of the



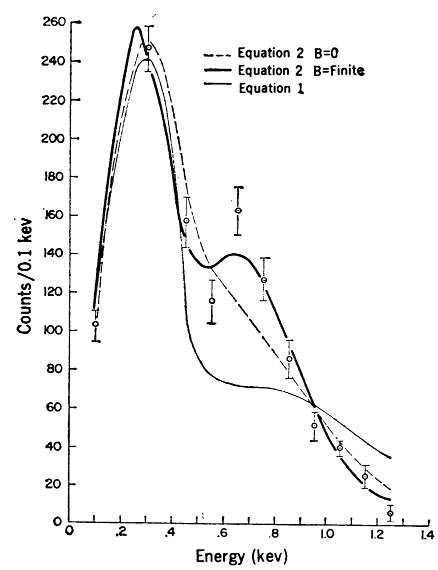


Fig. 3. The points are the pulse height distribution of counts from the Cygnus Loop as observed with this instrument. Smooth curves are the computed response of the instrument to Eq. 1 spectral functions and two cases of Eq. 2 spectral functions, $B = 0$, and B finite. The line of sight density of interstellar hydrogen is included in the trial functions as a free parameter.

Fig. 2 (left). Total x-ray data from Cygnus Loop superimposed upon a photograph of the filaments taken in red light with 48-inch Schmidt telescope (Mt. Wilson and Palomar Observatories). Field of view of the x-ray instrument is broad along direction of dashed lines.

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 $t_{1/2} = t_{\text{neb}}$, 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 radia-