SHOCK SPEED, COSMIC RAY PRESSURE, AND GAS TEMPERATURE IN THE CYGNUS LOOP

GREG SALVESEN\textsuperscript{1,2}, JOHN C. RAYMOND\textsuperscript{1}, AND RICHARD J. EDGAR\textsuperscript{1}

\textsuperscript{1} Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; salvesen@head.cfa.harvard.edu, jraymond@cfa.harvard.edu, edgar@head.cfa.harvard.edu
\textsuperscript{2} Department of Astronomy, The University of Michigan, 500 Church Street, Ann Arbor, MI 48109-1042, USA; salvesen@umich.edu

Received 2008 November 5; accepted 2009 July 14; published 2009 August 10

ABSTRACT

Upper limits on the shock speeds in supernova remnants can be combined with post-shock temperatures to obtain upper limits on the ratio of cosmic ray to gas pressure ($P_{\text{CR}}/P_{\text{g}}$) behind the shocks. We constrain shock speeds from proper motions and distance estimates, and we derive temperatures from X-ray spectra. The shock waves are observed as faint H$\alpha$ filaments stretching around the Cygnus Loop supernova remnant in two epochs of the Palomar Observatory Sky Survey (POSS) separated by 39.1 years. We measured proper motions of 18 nonradiative filaments and derived shock velocity limits based on a limit to the Cygnus Loop distance of $576 \pm 61$ pc given by Blair et al. for a background star. The Position Sensitive Proportional Counter (PSPC) instrument on-board ROSAT observed the X-ray emission of the post-shock gas along the perimeter of the Cygnus Loop, and we measure post-shock electron temperature from spectral fits. Proper motions range from 2\textdegree to 5\textdegree 4 over the POSS epochs and post-shock temperatures range from $kT \sim 100–200$ eV. Our analysis suggests a cosmic ray to post-shock gas pressure consistent with zero, and in some positions $P_{\text{CR}}$ is formally smaller than zero. We conclude that the distance to the Cygnus Loop is close to the upper limit given by the distance to the background star and that either the electron temperatures are lower than those measured from ROSAT PSPC X-ray spectral fits or an additional heat input for the electrons, possibly due to thermal conduction, is required.

Key words: cosmic rays – ISM: individual (Cygnus Loop) – shock waves – supernova remnants

Online-only material: color figures

1. INTRODUCTION

Supernova explosions are responsible for showering the surrounding interstellar medium (ISM) with heavy elements, influencing the distribution and composition of gas in the host galaxy. A typical supernova releases $\sim 10^{51}$ erg, sending a highly supersonic shock wave into its surroundings at speeds of up to 30,000 km s$^{-1}$ (Ghavamian et al. 2001). This expanding surge of energy heats and ionizes the neighboring gas out to hundreds of parsecs, initiating cloud collapse which leads to star formation and galactic evolution. Although a supernova is short-lived, the ejected remains propagate outward and interact with the ISM. These supernova remnants (SNRs) radiate over a large spectral range, transporting information about the blast wave morphology and local ISM.

The Cygnus Loop is a well known SNR whose distance is less than $576 \pm 61$ pc based on the distance to a star whose spectrum shows absorption features from shocked gas in the remnant (Blair et al. 2009). From a global perspective, its structure is governed by interactions with the surrounding inhomogeneous ISM. Despite its apparent spherical symmetry, both optical and X-ray observations suggest that the Cygnus Loop does not follow the simplified Sedov–Taylor morphology of an adiabatic blast wave expanding into a homogeneous, low-density medium. Instead, the blast wave deceleration is the result of encounters with dense, extended clouds distributed inhomogeneously in the pre-shocked gas (Levenson et al. 1997, 1998).

We focus on the nonradiative H$\alpha$ shock filaments, primarily in the northeastern Cygnus Loop, several of which were previously observed by Hester et al. (1994), Blair et al. (1999, 2005, 2009), Ghavamian et al. (2001), and Raymond et al. (2003). In a nonradiative shock, the cooling timescale of the hot shocked gas is much greater than the age of the shock. As the shocked gas has not had sufficient time to cool, post-shock radiation does not affect the shock evolution (McKee & Hollenbach 1980). Therefore, nonradiative shock filaments provide a laboratory for probing the conditions at the shock front before this information is lost by radiative or collisional processes. When a nonradiative shock encounters neutral gas, Balmer line emission is produced by the excitation of neutral hydrogen atoms prior to ionization. The resulting H$\alpha$ filaments trace the outer edge of the Cygnus Loop nonradiative blast wave as it expands through low-density, partially neutral gas. These H$\alpha$ filaments are useful for proper-motion measurements of shock fronts and investigations of shocked gas parameters.

SNR shock waves are believed to accelerate cosmic rays up to energies of $10^{15}$ eV and to be responsible for a large fraction of Galactic cosmic rays, implying an efficient process for particle acceleration. The theory of diffusive shock acceleration describes how charged particles (dominantly protons and electrons) passing back and forth across a shock front reach high energies, resulting in a power-law spectrum $\propto E^{-2}$ for cosmic rays above $\sim 10^9$ GeV (Blandford & Eichler 1987). This particle acceleration process requires a collisionless medium, as frequent collisions would return the velocity profile to Maxwellian.

The efficiency of energy conversion in SNR shocks into the acceleration of cosmic rays is highly dependent on shock structure and is a topic of active research. Theory indicates that the fraction of the energy dissipated in a shock going into cosmic rays is bistable, being either very small or $\sim 80\%$ (Malkov et al. 2000). Recent calculations of the evolution of SNR shocks show that the efficiency starts off low and evolves gradually to somewhat smaller values than that predicted by steady shock models (Caprioli et al. 2008). Synchrotron emission in the radio and X-ray bands provides direct observation of particle acceleration in SNRs; however, the majority of the SNR energy
going into particle acceleration is claimed by protons. Gamma rays are observed from a few SNRs, but it is still unclear whether they arise from electrons or protons (e.g., Berezhko & Völk 2006; Katz & Waxman 2008), so we must settle for inferences of the total cosmic ray acceleration efficiency through indirect methods. Warren et al. (2005) inferred shock compression ratios greater than 4 from the distance between the blast wave and the contact discontinuity in Tycho’s SNR. Their results suggest that the cosmic ray to gas pressure ratio, $P_{\text{CR}}/P_\text{G} > 1$, though projection effects might allow a smaller compression ratio (Cassam-Chenaï et al. 2008). High cosmic ray acceleration efficiencies have also been inferred from the low electron temperature in 1E102−72.6 (Hughes et al. 2000) and from shock wave precursors to Balmer line filaments (Smith et al. 1994; Hester et al. 1994).

In this paper, we find upper limits to $P_{\text{CR}}/P_\text{G}$ by combining measurements of post-shock electron temperature with the shock speed given by proper motions and distance upper limits. Our sample includes 18 nonradiative Hα shock segments dominantly in the northeastern rim of the Cygnus Loop. This sample, although limited by the uncertainties in proper motion, temperature, and distance, provides constraints on $P_{\text{CR}}/P_\text{G}$. Several positions show apparently negative values of $P_{\text{CR}}$, and we discuss the uncertainties in temperature and distance and the possibility of additional electron heating that could account for that nonphysical result.

2. OBSERVATIONS AND DATA REDUCTION

We observe regions in the northern, eastern, and western Cygnus Loop over optical and X-ray bands. The Palomar Observatory Sky Survey (POSS) obtained the optical data, and the ROSAT Position Sensitive Proportional Counter (PSPC) obtained the X-ray data. We reduced two epochs of optical data for proper-motion measurements. The X-ray data were obtained within two years of the more recent optical epoch. We matched all data epochs using the world coordinate system (WCS) to ensure consistency during optical and X-ray analysis.

2.1. POSS Optical Data Reduction

The POSS observed the Cygnus Loop over two epochs spanning 39.1 years. These photographic plates have been digitized by the Space Telescope Science Institute (STScI) and are publicly archived as the Digitized Sky Survey. We selected the filtered surveys whose transmission coefficient peaked near Hα ($\lambda = 6562.8$ Å), corresponding to surveys POSS-I E (red) and POSS-II F (red), to ensure detection of Hα shock filaments along the Cygnus Loop perimeter. We refer to the 1953 June 15 observations as POSS-I and the 1992 July 24 observations as POSS-II, with exposure times of 45.0 and 120 minutes, respectively. The pixel scales of the digitized POSS-I and POSS-II plates are 1′′7 and 1′′0, respectively.

We analyzed proper motions of 18 Hα shock filaments which define the perimeter of the Cygnus Loop. We used IDL and SAOImage DS9 for subsequent image analysis. From each POSS epoch, we hand selected a subimage containing the filament of interest surrounded by reference background and foreground stars based on a common WCS (J2000) position. POSS-I and POSS-II pixel scales were resampled to 0′′1 using bilinear interpolation between grid points. Each set of subimages was rotated appropriately to account for precession effects during the time between observations. An additional rotation was incorporated to align the shock along the image axis for the proper-motion analysis. Two-dimensional cross-correlation methods determined an optimal fine-tuned pixel shift to overlap the POSS-I and POSS-II subimages. In the resulting images the background stars are stationary, leaving the propagating shock for analysis. All image manipulation was made relative to the POSS-I plate in an attempt to maintain the original integrity of the data.

2.2. ROSAT PSPC X-ray Data Reduction

The Cygnus Loop X-ray data we analyzed were obtained with the PSPC detector on-board the ROSAT observatory. The observation timeline spans from 1992 November 4 to 1994 June 3 with three separate pointings targeting three locations. Table 1 lists the ROSAT PSPC observations relevant to our X-ray post-shock analysis of the Cygnus Loop. All observed data sets are publicly archived through the HEASARC.

To prepare the ROSAT PSPC data for analysis, spectral regions were extracted from the PSPC events files requiring a minimum of 1200 counts within each region. Source and background spectra were extracted and truncated to Pulse Invariant (PI) channels 0–255 using xselect version 2.4. We filter PSPC spectra to accept good events and, since we will be using $\chi^2$ statistics, we require a minimum of 20 counts per bin using the FTOOL grppha. We extracted X-ray emitting regions extending from 25″ to 100″ behind each Hα filament of interest. As discussed below, we avoided the region within 25″ where the gas is significantly out of ionization equilibrium. Background spectra were taken outside the outer shock front and scaled by the ratio of the areas of the extraction regions. PSPC response matrices were obtained from the legacy.gsfc.nasa.gov anonymous ftp archive and ancillary response files (ARFs) were generated using the FTOOL pcarf as outlined by Turner (1996). The resulting spectra were fitted with XSPEC version 11.3.2 (Arnaud 1996). The PSPC detector is calibrated over the 0.1–2 keV soft X-ray energy band (Prieto et al. 1996). All spectra were fitted in the 0.1–1.1 keV band as more energetic photons were not typically detected. The X-ray errors presented in this paper are at the 90% confidence level obtained with the XSPEC error command unless otherwise indicated.

3. ANALYSIS AND RESULTS

We surveyed 18 shock filaments, each of length 120″, spanning the eastern, northern, and western Cygnus Loop outer shell which is defined by its characteristic Hα emission. For each filament, we measured proper motion by comparing two epochs of POSS red digitized plates and post-shock gas temperature from spectral fits to ROSAT PSPC X-ray data, assuming ionization equilibrium. Adopting the most recent distance upper limit to the Cygnus Loop of 576 ± 61 pc (Blair

| Table 1 | Cygnus Loop ROSAT PSPC Observation Parameters |
|---------|---------------------------------------------|
| Name    | $\alpha_{J2000}$ | $\delta_{J2000}$ | Date (UT) | Exposure (ks) |
| rp500034a01 | 20 55 02.4 | +32 07 12.0 | 1992 Nov 4 | 12.0 |
| rp500267a00 | 20 56 21.6 | +30 24 00.0 | 1993 Nov 14 | 9.24 |
| rp500268a00 | 20 45 40.8 | +31 02 24.0 | 1994 Jun 3 | 9.75 |

Notes. The coordinates listed describe the target location for a particular ROSAT PSPC pointing. Units of right ascension are hours, minutes, and seconds. Units of declination are degrees, arcminutes, and arcseconds. We adopt this system of units throughout this paper.
et al. 2009), we constrain the ratio of cosmic ray to gas pressure. We discuss our methodology, the uncertainties in proper motion, temperature, and distance, and the results below.

3.1. Proper Motion

3.1.1. Proper-motion Measurements from POSS Epoch Comparisons

We determine the proper motion of 18 regions enclosing Hα shock filaments primarily along the northeastern perimeter of the Cygnus Loop. Figures 1–6 show POSS-II images indicating the locations and dimensions of the extracted regions. In all images, north is at the top and east points to the left. Each extracted slit, outlined in blue with a corresponding identification number, has dimensions 25″ × 120″ and is positioned parallel to a nonradiative Hα filament. The overlap seen between some filaments is necessary to enclose the entire region of interest while also adhering to the selection criteria described below. We acknowledge potential duplication resulting from overlap but consider this a minor concern as each proper-motion measurement is made independently. Table 2 lists right ascension and declination relative to POSS-I for each of the 18 regions enclosing a nonradiative filament. Regions are labeled by a filament number which increments with decreasing declination. We adopted the following Hα filament selection criteria applicable to both POSS-I and POSS-II images.

1. Filaments must be bright relative to the local background.
2. Selected filaments must be continuous with no local branching structure.
3. Filaments must not precede another shock wave or strong optical emission within 100″ to provide an extractable ROSAT PSPC post-shock region for X-ray temperature analysis.
4. A region enclosing a filament is not overwhelmed by stars.
5. Filament geometry appears to be rigid and planar over both epochs allowing for uniform shock expansion in one dimension.

Each filament is hand selected and both epochs of images are reduced as described in Section 2.1 to align the shock along the image axis. Rectangular regions 25″ × 120″ parallel
The coordinates listed represent the right ascension and declination at the center of the extracted filament. The measured proper motions are derived from comparing POSS-I and POSS-II images observed 39.1 years apart. Errors on proper motion do not include a \( \pm 0.01 \) uncertainty from image alignment. Shock speed \( v_s \) is calculated from the product of proper motion and distance using the upper limits of proper motion + uncertainty and \( 576 + 61 = 637 \) pc (Blair et al. 2009). All cosmic ray to gas pressure ratio calculations are based on these conservative upper limits. Minimum distances to the Cygnus Loop based on our measurements assume \( P_{\text{CR}} / P_g = 0 \) with an upper limit on proper motion and lower limit on temperature. We compare results from individual X-ray temperature fits with the XSPEC models apec and raymond.

### Table 2

| Filament ID | \( \alpha_{2000} \) | \( \delta_{2000} \) | Proper Motion (arcsecond/39.1 years) | \( v_{\text{max}} \) (km s\(^{-1}\)) | \( (P_{\text{CR}} / P_g)_{\text{apec}} \) | \( (P_{\text{CR}} / P_g)_{\text{raymond}} \) | \( (P_{\text{CR}} / P_g)_{\text{raymond}} \) | \( d_{\text{raymond}} \) |
|-------------|-----------------|-----------------|-------------------------------|-------------------|-----------------|-----------------|-----------------|-----------------|
| 1           | 20 51 23.9      | 32 24 22.5      | 5'1 ± 0'2                     | 403               | -0.032          | 0.408           | 0.111           | 1.274           | 422             |
| 2           | 20 51 29.9      | 32 24 21.8      | 5'4 ± 0'2                     | 433               | 0.091           | 0.625           | 0.190           | 0.637           | 498             |
| 3           | 20 51 38.6      | 32 24 14.5      | 5'2 ± 0'2                     | 416               | -0.032          | 0.501           | 0.053           | 0.582           | 507             |
| 4           | 20 54 13.1      | 32 21 14.0      | 2'7 ± 0'2                     | 225               | -0.723          | -0.616          | -0.698          | -0.560          | 960             |
| 5           | 20 54 26.2      | 32 19 36.5      | 3'4 ± 0'2                     | 278               | -0.543          | -0.344          | -0.473          | -0.325          | 775             |
| 6           | 20 54 43.4      | 32 16 04.0      | 4'1 ± 0'2                     | 333               | -0.337          | -0.004          | 0.638           | -0.239          | 0.550           | 512             |
| 7           | 20 55 06.3      | 32 10 03.8      | 3'0 ± 0'1                     | 240               | -0.587          | -0.496          | 0.897           | -0.561          | -0.193          | 709             |
| 8           | 20 55 14.7      | 32 07 38.9      | 3'4 ± 0'1                     | 274               | -0.507          | -0.428          | 0.843           | -0.456          | -0.397          | 821             |
| 9           | 20 55 18.9      | 32 06 58.0      | 3'7 ± 0'1                     | 294               | -0.384          | -0.275          | 0.748           | -0.338          | -0.259          | 740             |
| 10          | 20 55 34.6      | 32 01 40.2      | 3'5 ± 0'1                     | 279               | -0.400          | -0.317          | 0.771           | -0.383          | 0.026           | 629             |
| 11          | 20 55 44.9      | 31 59 43.8      | 3'1 ± 0'2                     | 254               | -0.507          | -0.432          | 0.845           | -0.424          | 0.066           | 617             |
| 12          | 20 55 51.8      | 31 57 34.8      | 4'0 ± 0'2                     | 319               | -0.231          | -0.115          | 0.677           | -0.203          | 0.253           | 569             |
| 13          | 20 55 56.5      | 31 55 55.1      | 4'2 ± 0'7                     | 375               | -0.120          | 0.256           | 0.568           | 0.020           | 1.034           | 447             |
| 14          | 20 57 20.2      | 31 37 32.4      | 4'3 ± 0'1                     | 342               | -0.176          | 0.030           | 0.628           | -0.127          | 0.299           | 559             |
| 15          | 20 54 11.9      | 31 03 50.0      | 3'4 ± 0'1                     | 272               | -0.415          | -0.351          | 0.791           | -0.329          | -0.182          | 704             |
| 16          | 20 55 15.3      | 31 01 41.4      | 3'3 ± 0'1                     | 264               | -0.492          | -0.443          | 0.854           | -0.470          | -0.428          | 842             |
| 17          | 20 56 37.4      | 30 08 34.4      | 4'5 ± 0'1                     | 358               | -0.054          | 0.049           | 0.622           | 0.013           | 0.434           | 532             |
| 18          | 20 56 34.8      | 30 06 27.8      | 4'8 ± 0'1                     | 379               | -0.044          | 0.237           | 0.573           | 0.099           | 0.707           | ...             |

Notes. The coordinates listed represent the right ascension and declination at the center of the extracted filament. The measured proper motions are derived from comparing POSS-I and POSS-II images observed 39.1 years apart. Errors on proper motion do not include a \( \pm 0.01 \) uncertainty from image alignment. Shock speed \( v_s \) is calculated from the product of proper motion and distance using the upper limits of proper motion + uncertainty and \( 576 + 61 = 637 \) pc (Blair et al. 2009). All cosmic ray to gas pressure ratio calculations are based on these conservative upper limits. Minimum distances to the Cygnus Loop based on our measurements assume \( P_{\text{CR}} / P_g = 0 \) with an upper limit on proper motion and lower limit on temperature. We compare results from individual X-ray temperature fits with the XSPEC models apec and raymond.
data. The post-shock gas must not encounter a trailing blast wave within $\sim 100''$ to validate the assumption of ionization equilibrium required by our X-ray temperature analysis. While there are numerous, well-defined Hα filaments delineating the northeastern Cygnus Loop, we only measure proper motions of those where the post-shock gas has adequate time to reach thermal and ionization equilibrium, allowing us to constrain cosmic ray to gas pressure.

### 3.1.2. Proper-motion Uncertainty

The statistical uncertainties in the proper motions are determined by the measurement procedure to be 0''1 to 0''2 for all but one of the filaments. Additional systematic uncertainty could arise from the cross-registration of the images from the different epochs, though that error should be small because of the large number of stars used in the cross-correlation. Indeed, we have compared the positions of individual stars in the different epochs and find them to differ by considerably less than an arcsecond. It is also possible that changes in brightness among different regions within an unresolved filamentary structure (see Blair et al. 1999, 2005) could cause errors in the proper motion. We expect such errors to be small, and measurement of 18 positions limits the impact of any such errors. Thus while there is a small systematic error, it is unimportant because the uncertainties in temperature and distance dominate.

We can also compare with other proper-motion determinations. Shull & Hippelein (1991) reported proper motions of $1''3$ to $14''6$ century$^{-1}$, with the latter value for a Balmer line filament close to our position 14, and Hester et al. (1986) found $7''$ century$^{-1}$ for two Balmer line filaments in the northeast, one of which was observed by Blair et al. (1999, 2005). Blair et al. (1999) observed a nonradiative Hα filament in the Cygnus Loop ($\alpha_{2000} = 20^h56^m2.7^s$, $\delta_{2000} = 31^\circ56'39''$) propagating into relatively dense neutral gas (see Figure 3). The filament proper motion was measured as $3''6 \pm 0''5$ by comparing POSS-I and Hubble Space Telescope (HST) images taken $\sim 44.3$ years apart using stars as stationary reference points. However, the two reference stars used changed apparent position by 0''5 and 0''2, increasing proper-motion uncertainty. We measured this same filament with the method described in Section 3.1.1 by

![Figure 7](image-url)  Typical region selection process across an Hα filament. The shock is aligned along the image axis and enclosed by a $25'' \times 120''$ rectangular region. The black sub-regions are selected for analysis. The sub-regions enclosed by the white lines are dominated by stars; therefore, they are not extracted for proper-motion analysis. Identical sub-regions are extracted for both POSS epochs and the columns of the remaining starless regions are totaled for cross-correlation comparisons. This selection process was applied to each filament. This particular image illustrates the results for filament 7.

![Figure 8](image-url)  Histogram distribution of proper-motion measurements after 1000 bootstrap iterations. The bins are 0''1 wide and the results are normalized to unity. The 90% confidence range in proper motion is represented by $\sigma$, given by multiplying the standard deviation by 1.645. A bootstrap sampling method was applied to each filament. This particular distribution illustrates the results for filament 7.

![Figure 9](image-url)  Spread in correlation coefficient for one iteration between sampled POSS-I and POSS-II subregions contributing to the histogram in Figure 8. Maximization of the correlation coefficient determines the optimal proper motion of the filament. This method for measuring proper motion was applied to each filament. This particular distribution illustrates the results for filament 7.
combining POSS-I and two different POSS-II observations taken on 1992 July 24 and 1995 August 25 yielding proper motions of $2.6 \pm 0.1$ and $3.1 \pm 0.1$, respectively. Assuming a constant shock speed, we extrapolate these measurements to $3'0$ and $3'2$ at the time of the 1997 November 16 HST observation. These two proper-motion measurements and that of Blair et al. (1999) were made relative to the POSS-I 1953 June 15 plate, providing three independent measurements.

Blair et al. (2005) revisited this same filament and measured a proper motion of $0.28 \pm 0.03$ by comparing two epochs of HST images taken ~4 years apart. Assuming no deceleration, the proper motions measured by Blair et al. (1999, 2005) are $0.081 \pm 0.011$ yr$^{-1}$ and $0.070 \pm 0.008$ yr$^{-1}$, respectively. We extrapolate our two measurements quoted above and find proper motions of $0.066 \pm 0.002$ yr$^{-1}$ and $0.073 \pm 0.002$ yr$^{-1}$ for the 1992 July 24 and 1995 August 25 POSS-II observations, respectively. Therefore, marginal agreement with the results of Blair et al. (1999) is replaced by excellent agreement with the proper-motion measurements of Blair et al. (2005). Given that these results are within the limits presented in Blair et al. (1999, 2005) when reference star position changes are included, we consider our proper-motion methodology justified. Although the HST image reveals intricate substructure, if we assume that the substructure of a particular filament has not dramatically changed over the POSS epochs, the poor resolution of the POSS plates smoothes these features and should give accurate results.

3.2. Post-shock Temperature

3.2.1. Temperature Measurements from ROSAT Spectral Fitting

We extracted PSPC spectra of four $25'' \times 120''$ strips stacked behind and parallel to each filament for measurements of post-shock gas temperature behavior over $100''$. The single-temperature models apec and raymond show low post-shock temperature in the first $\sim 25''$ behind each filament. Within the $100''$ post-shock region, the fitted temperature is consistently lower within the $25''$ region immediately behind the shock in agreement with Raymond et al. (2003). This suggests departure from ionization equilibrium immediately following the shock because the gas has had insufficient time to ionize.

We show below that the post-shock gas reaches ionization equilibrium after $25''$, so we extracted PSPC X-ray spectra of a $75'' \times 120''$ region extending from $25''$ to $100''$ behind each filament. Corresponding background regions were selected outside of the X-ray shock front and scaled, and source and background regions reduced as discussed above (Section 2.2.2). Figures 10–12 show the locations of extracted PSPC X-ray regions for all of the Hα filaments we considered, where north is at the top and east is toward the left.

All of our spectral fits used the XSPEC model phabs to account for absorption of interstellar gas along the line of sight combined with a hot plasma X-ray emission model. The nominal interstellar column density value was $N_H = 1.5 \times 10^{20}$ cm$^{-2}$, but it was allowed to vary in all model fits (Raymond et al. 2003; Decourchelle et al. 1997). For all the soft X-ray fits presented in this paper, $N_H$ is constrained within $\sim 1 - 5 \times 10^{20}$ cm$^{-2}$. The $kT_e$ and $N_H$ parameters in the model are highly (and negatively) correlated, in the sense that a very small change in the temperature yields a large change in $N_H$. The fluctuations in $N_H$ are likely not significant.

Ghavamian et al. (2001) measured Hα velocity line widths of a nonradiative shock located between filaments 5 and 6 in the northeastern Cygnus Loop and found good electron–ion
equilibration, $T_e/T_i \sim 0.7$–1.0, in the post-shock region. We have assumed $T_e = T_i$ throughout our analysis.

Single-temperature models and standard cosmic abundance assumptions are challenged by claims of bimodal temperature regions and depleted abundances (e.g., Nemes et al. 2008). Three fits were made to each PSPC X-ray spectrum: (1) a single-temperature fit assuming cosmic abundances (Anders & Grevesse 1989), (2) a single-temperature fit assuming depleted abundances, and (3) a double-temperature fit assuming cosmic abundances. Depleted abundance fits fixed C, Mg, Al, Si, Ca, Fe, and Ni to 10% cosmic values on the basis that these elements are locked up in grains. Other abundances were fixed to cosmic. The subscript “cos” refers to single-temperature model fits $\chi^2$/v with abundances fixed to cosmic. We allowed $N_H$ to vary from an initial value of $1.5 \times 10^{20}$ cm$^{-2}$. We stress that the errors listed in the table are generated in XSPEC and are not representative of actual uncertainties based on the variation in best-fit values when comparing similar models. Fits with no errors or parameters listed are unphysical or limited by $\chi^2$ statistics.

Table 3 lists the resulting best-fit temperatures and $\chi^2$/v values using the XSPEC models:

1. phabs $\times$ apec,  
2. phabs $\times$ vapec,  
3. phabs $\times$ (apec $+$ vapec),

while Table 4 lists the same parameters using the XSPEC models:

1. phabs $\times$ raymond,  
2. phabs $\times$ vraymond,  
3. phabs $\times$ (raymond $+$ raymond).

Temperature estimates are required for calculations of the cosmic ray to gas pressure ratio downstream. The double-temperature models consistently produce better fits based on $\chi^2$ statistics, and $T_{\text{low}}$ remains continuous and consistent along adjacent filaments. However, there is no glaring physical reason to require two downstream temperatures. Hester et al. (1994) discuss how reflection of a blast wave from a dense cloud will enhance the temperature, and this may apply to the parts of the Cygnus Loop where the optical emission is bright, but we have avoided those complicated areas for this analysis. As discussed below, temperatures also depend on the assumed set of elemental abundances. We estimate the post-shock electron temperature as $T_{\text{e}}$ from the fits assuming cosmic abundances since they best represent the data. Lower limits on temperature are taken as $T_{\text{low}}$ from the double-temperature models, as this gives conservative lower limits to the gas pressure. Cosmic ray to gas pressure is inferred and an upper limit is calculated based on these temperatures and measured proper motions. Temperatures from both apec and raymond models are independently analyzed for all 18 post-shock regions as a consistency check on temperature measurements.

3.2.2. X-ray Temperature Uncertainty

The derivation of temperatures from X-ray data, especially low-resolution X-ray data such as that provided by ROSAT, is fraught with systematic errors. In this section, we attempt to quantify some of those errors.

Our extraction regions were chosen to provide at least 1200 good X-ray events in each so that the statistical errors are minimal.

We have made two assumptions in our fitting: equilibrium ionization and cosmic abundances.

| Filament ID | $T_{\text{cos}}$ (eV) | $N_{H,\text{cos}}$ ($10^{20}$ cm$^{-2}$) | $(\chi^2/v)_{\text{cos}}$ | $T_{\text{dep}}$ (eV) | $(\chi^2/v)_{\text{dep}}$ | $T_{\text{low}}$ (eV) | $T_{\text{high}}$ (eV) | $(\chi^2/v)_{\text{double}}$ |
|-------------|----------------------|----------------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|--------------------------|
| 1           | 187$^{+5}_{-6}$     | $2.4^{+0.2}_{-0.2}$              | 1.65                     | 162$^{+10}_{-10}$     | 3.37                   | 137                    | 536                    | 1.13                     |
| 2           | 192$^{+5}_{-6}$     | $2.0^{+0.2}_{-0.2}$              | 1.80                     | 198$^{+10}_{-10}$     | 3.01                   | 137                    | 602                    | 1.28                     |
| 3           | 198$^{+5}_{-6}$     | $2.5^{+0.2}_{-0.2}$              | 1.44                     | 230$^{+10}_{-10}$     | 2.47                   | 137                    | 336                    | 1.16                     |
| 4           | 190$^{+5}_{-6}$     | $2.1^{+0.2}_{-0.2}$              | 0.96                     | 194$^{+9}_{-9}$       | 1.86                   | 157                    | 454                    | 0.85                     |
| 5           | 181$^{+5}_{-6}$     | $2.5^{+0.2}_{-0.2}$              | 1.48                     | 159$^{+5}_{-5}$       | 3.21                   | 140                    | 605                    | 1.06                     |
| 6           | 179$^{+4}_{-5}$     | $2.1^{+0.1}_{-0.1}$              | 2.33                     | 151                   | 5.75                   | 132                    | 380                    | 1.60                     |
| 7           | 154$^{+4}_{-5}$     | $2.6^{+0.2}_{-0.2}$              | 2.22                     | 119                   | 5.95                   | 136                    | 541                    | 1.53                     |
| 8           | 170$^{+3}_{-5}$     | $1.2$                             | 1.26                     | 118$^{+4}_{-4}$       | 3.44                   | 156                    | 661                    | 1.06                     |
| 9           | 159$^{+5}_{-6}$     | $1.7^{+0.2}_{-0.2}$              | 1.45                     | 115$^{+4}_{-4}$       | 3.63                   | 141                    | 656                    | 1.14                     |
| 10          | 146                 | $2.1$                             | 5.59                     | 80.8                  | 10.7                   | 135                    | ...                    | 3.90                     |
| 11          | 139                 | $1.9$                             | 5.07                     | 80.8                  | 9.92                   | 135                    | 690                    | 3.95                     |
| 12          | 145$^{+3}_{-3}$     | $1.1^{+0.1}_{-0.1}$              | 2.91                     | 80.8                  | 7.18                   | 136                    | 685                    | 1.55                     |
| 13          | 139                 | $1.7$                             | 5.03                     | 80.8                  | 9.34                   | 133                    | 863                    | 3.40                     |
| 14          | 159$^{+4}_{-5}$     | $1.8^{+0.3}_{-0.3}$              | 1.48                     | 115$^{+4}_{-4}$       | 3.14                   | 135                    | 727                    | 0.89                     |
| 15          | 140$^{+4}_{-5}$     | $2.1^{+0.2}_{-0.2}$              | 2.81                     | 80.8                  | 5.24                   | 135                    | 812                    | 2.29                     |
| 16          | 150$^{+3}_{-3}$     | $2.4^{+0.1}_{-0.1}$              | 1.02                     | 86.8                  | 1.91                   | 148                    | 692                    | 1.03                     |
| 17          | 152$^{+3}_{-3}$     | $4.2^{+0.6}_{-0.6}$              | 1.19                     | 146$^{+9}_{-9}$       | 1.91                   | 145                    | 159                    | 1.24                     |
| 18          | 169$^{+3}_{-3}$     | $3.8^{+0.7}_{-0.7}$              | 1.32                     | 155$^{+3}_{-3}$       | 1.88                   | 138                    | 633                    | 1.24                     |

Notes. ROSAT PSPC X-ray spectral parameters corresponding to fits behind each filament with the XSPEC model apec. The subscript “cos” refers to single-temperature model fits $\chi^2$/v with abundances fixed to cosmic. We allowed $N_H$ to vary from an initial value of $1.5 \times 10^{20}$ cm$^{-2}$. We stress that the errors listed in the table are generated in XSPEC and are not representative of actual uncertainties based on the variation in best-fit values when comparing similar models. Fits with no errors or parameters listed are unphysical or limited by $\chi^2$ statistics.
Table 4
X-ray Spectral Fit Parameters with the raymond Model

| Filament ID | T<sub>cos</sub> (eV) | N<sub>H,cos</sub> (10<sup>20</sup> cm<sup>−2</sup>) | (χ<sup>2</sup>/ν)<sub>cos</sub> | T<sub>dep</sub> (eV) | (χ<sup>2</sup>/ν)<sub>dep</sub> | T<sub>low</sub> (eV) | T<sub>high</sub> (eV) | (χ<sup>2</sup>/ν)<sub>double</sub> |
|------------|-------------------|-----------------|------------------|--------------|------------------|--------------|--------------|-----------------|
| 1          | 163<sup>±2</sup>  | 3.5<sup>±0.5</sup> | 1.69 | 453<sup>±22</sup> | 157               | 84.8         | 360          | 0.93            |
| 2          | 176<sup>±2</sup>  | 3.0<sup>±0.2</sup> | 1.89 | 485<sup>±24</sup> | 170               | 136          | 702          | 1.27            |
| 3          | 182<sup>±2</sup>  | 2.9<sup>±0.2</sup> | 1.47 | 487<sup>±26</sup> | 2.31             | 130          | 356          | 1.13            |
| 4          | 174<sup>±1</sup>  | 2.8<sup>±0.6</sup> | 1.03 | 444<sup>±16</sup> | 1.93             | 137          | 448          | 0.84            |
| 5          | 157<sup>±3</sup>  | 3.6<sup>±0.4</sup> | 1.51 | 432<sup>±10</sup> | 2.19             | 136          | 776          | 1.06            |
| 6          | 156<sup>±3</sup>  | 3.2<sup>±0.2</sup> | 2.17 | 427<sup>±13</sup> | 3.18             | 84.8         | 266          | 1.28            |
| 7          | 145<sup>±3</sup>  | 3.9<sup>±0.2</sup> | 2.02 | 372<sup>±12</sup> | 2.85             | 84.9         | 292          | 1.09            |
| 8          | 154<sup>±2</sup>  | 2.1<sup>±0.2</sup> | 1.16 | 430<sup>±9</sup>  | 2.29             | 148          | ...           | 1.08            |
| 9          | 148<sup>±4</sup>  | 2.5<sup>±0.2</sup> | 1.34 | 415<sup>±17</sup> | 2.05             | 138          | ...           | 1.11            |
| 10         | 142               | 2.8               | 5.19 | 373<sup>±10</sup> | 3.23             | 89.9         | 539          | 2.60            |
| 11         | 119<sup>±5</sup>  | 3.6<sup>±0.4</sup> | 4.61 | 326<sup>±8</sup>  | 2.32             | 71.9         | 449          | 1.67            |
| 12         | 140<sup>±3</sup>  | 1.9<sup>±0.1</sup> | 2.58 | 379<sup>±10</sup> | 2.08             | 96.1         | 425          | 1.04            |
| 13         | 120<sup>±3</sup>  | 3.2<sup>±0.4</sup> | 4.63 | 366<sup>±11</sup> | 2.98             | 82.1         | 627          | 1.84            |
| 14         | 150<sup>±3</sup>  | 2.6<sup>±0.3</sup> | 1.34 | 431<sup>±21</sup> | 1.17             | 107          | 670          | 0.84            |
| 15         | 122<sup>±3</sup>  | 3.7<sup>±0.6</sup> | 2.66 | 114<sup>±3</sup>  | 2.83             | 107          | 704          | 1.81            |
| 16         | 144<sup>±7</sup>  | 0.9<sup>±0.2</sup> | 1.02 | 133<sup>±5</sup>  | 1.16             | 144          | 145          | 1.06            |
| 17         | 142<sup>±3</sup>  | 3.3<sup>±0.3</sup> | 1.22 | 143<sup>±7</sup>  | 1.39             | 106          | 693          | 1.03            |
| 18         | 147<sup>±5</sup>  | 5.2<sup>±0.6</sup> | 1.32 | 150<sup>±10</sup> | 1.52             | ...          | 147          | 1.39            |

Notes. ROSAT PSPC X-ray spectral parameters corresponding to fits behind each filament with the XSPEC model raymond. The subscript “cos” refers to single-temperature model fits phabs × raymond with abundances fixed to cosmic. The subscript “dep” refers to double-temperature model fits phabs × raymond with depleted abundances fixed to 10% cosmic. The subscript “double” refers to double-temperature model fits phabs × (raymond+raymond) with abundances fixed to cosmic. We allowed N<sub>H</sub> to vary from an initial value of 1.5 × 10<sup>20</sup> cm<sup>−2</sup>. We stress that the errors listed in the table are generated in XSPEC and are not representative of actual uncertainties based on the variation in best-fit values when comparing similar models. Fits with no errors or parameters listed are unphysical or limited by χ<sup>2</sup> statistics.

To investigate these, we produced spectra using the nonequilibrium ionization (NEI) shock code of Cox & Raymond (1985) for a shock with v<sub>s</sub> = 350 km s<sup>−1</sup>, which is typical of the velocities shown in Table 2, and a pre-shock density of 0.25 cm<sup>−3</sup>, which is typical of values determined from X-ray and UV observations (e.g., Raymond et al. 2003). The shock code computes the time-dependent (NEI) ionization state of the shocked gas, so by fitting these models with ionization equilibrium spectra we can evaluate the error involved in the assumption of ionization equilibrium. The alternative would be to use an NEI model such as vpshock, but that introduces an additional free parameter that cannot be constrained well with the ROSAT data. We then integrated the surface brightness to distances which correspond to 25, 50, 75, and 100″ behind the shock. The resulting spectra were multiplied by a photoelectric absorption model with N<sub>H</sub> = 1.5 × 10<sup>20</sup> cm<sup>−2</sup>, convolved with the ROSAT response, and used with the XSPEC fakemt command to generate Poisson-sampled random spectra consistent with the shock model. We did this for both cosmic and depleted abundances. We then fit these spectra with a cosmic abundance, single-temperature raymond model, assuming equilibrium ionization. We find that for the cosmic abundance cases, the fitted temperature underestimated the true input temperature by 3%, which is a small effect. The first zone, within 25″ of the shock, had a much lower fitted temperature. Accordingly, in our fitting of the Cygnus Loop data, we have ignored the first 25″ bin.

Similarly, if we model a shock with depleted abundances, we find the spectrum is harder than with cosmic abundances. This is because much of the 1/4 keV band flux is provided by lines of Si, Mg, and Fe, while the 3/4 keV band flux at these shock speeds and temperatures is provided mostly by O and Ne which are undepleted even in dusty interstellar plasmas. Fitting such a spectrum with a model which presumes cosmic abundances will overestimate the temperature to produce the harder spectrum. However, the model allows the column density of neutrals along the line of sight to vary, and this can compensate and even overcompensate for the excess emission in the soft band predicted by the cosmic abundance model, so that the temperature can be underestimated. Overall, we find that fitting a depleted shock spectrum to a cosmic abundance equilibrium model underestimates the temperature by about 11%.

The large quantity of atomic physics data which go into simulations of the spectra of hot, collisional plasmas all have uncertainties as well. In order to assess these effects, we...
Figure 14. Representative example of a ROSAT PSPC single-temperature apec model fit with C, Mg, Al, Si, Ca, Fe, and Ni abundances depleted to 10% cosmic values and fixed. The rational for depletion is that these elements may be locked up in grains. This particular plot illustrates the results for filament 7.

Figure 15. Representative example of a ROSAT PSPC double-temperature apec model fit with abundances fixed to cosmic values. In most cases, a bimodal temperature distribution was statistically significant, providing motivation to investigate this in future works. This particular plot illustrates the results for filament 7.

have fitted the spectra with both the apec (Desai et al. 2005; Smith et al. 2001) and raymond (Raymond & Smith 1977, as updated) models. There is a systematic difference in the fitted temperatures of single-temperature, cosmic abundance models, in the sense that the raymond model gives a fitted temperature about 0.15 ± 0.05 keV lower than the apec model does. This is probably because apec includes only emission lines for which reliable atomic data are available, while raymond includes emission lines which must be present, but for which the atomic data are more uncertain. This mainly affects the Mg, Si, S, and Fe lines in the 1/4 keV band.

Accordingly, we discuss lower limits to the electron temperatures. We use the low temperatures from the two-temperature, cosmic abundance fits as conservative lower limits to the temperature and therefore to the gas pressure. Figure 16 shows the range of $P_{CR}/P_G$ for each filament. Even so in many cases we find that they imply upper limits to the cosmic ray pressure which are negative, a clearly unphysical situation.

3.3. Other Temperature Determinations for the Cygnus Loop

The Cygnus Loop is one of the most studied SNRs in the Galaxy, and each X-ray observatory in turn has observed it. Although ROSAT is limited by poor spectral resolution, our

requirement to simultaneously measure proper motions and post-shock temperatures is met by the epoch overlap between POSS and ROSAT observations; thus, justifying the choice to use ROSAT data for our X-ray analysis. Furthermore, the better low-energy sensitivity of ROSAT compared to subsequent observatories makes it well suited for studying the relatively low-temperature gas in the Cygnus Loop. Each observatory has its own strengths and weaknesses, and the ensemble of results helps to constrain the systematics of any one observation. Many of these observations cover the area we study, with special attention on the NE rim.

Miyata et al. (2007) analyze Suzaku observations of a field in the NE. Their superior spectral resolution in the 0.3–2 keV band shows many lines of elements such as C, N, O, Ne, and Mg. They fit two-temperature models to the spectra and find the higher temperature component, which is constrained by the lines in the spectrum, has $kT$ greater than about 0.2 keV.

Tsunemi et al. (2007) analyze data from a series of XMM-Newton pointings across the Cygnus Loop from northeast to southwest. They also fit two-temperature models to narrow concentric slices of the remnant. Their lower temperature (which they identify as the forward shock) is always greater than $kT = 0.2$ keV.

The Chandra observatory has also observed the NE rim. Katsuda et al. (2008) report fits to the XSPEC v$	au$ho_c model, which allows for NEI effects, and variable abundances. They also obtain fitted temperatures uniformly in excess of 0.2 keV.

It therefore seems that these high temperatures are quite robust features of the X-ray emission from the NE rim of the Cygnus Loop. Chandra’s high spatial resolution, XMM-Newton’s large collecting area, and Suzaku’s superior spectral resolution all lead to the same conclusion we obtain from the ROSAT data: $kT$ values of 150 eV or higher are ubiquitous in the nonradiative filaments of the Cygnus Loop.

3.4. Distance

The distance to the Cygnus Loop is a substantial uncertainty, and our measurements can be used to obtain a lower limit to the distance. Minkowski (1958) obtained the canonical
value of 770 pc from the velocity ellipse and proper motions, though Braun & Strom (1986) used the same data to obtain 460 ± 160 pc using the mean expansion velocity instead of the extreme. Shull & Hipplelein (1991) obtained a distance of 600 pc based on Fabry-Perot scans of a large number of fields in the Cygnus Loop, but with a range of 300 to 1200 pc. Sakhibov & Smirnov (1983) also compared proper motions and radial velocities to obtain an estimate of 1400 pc. Though the method of comparing radial velocities and proper motions relies only upon the assumptions of symmetric expansion and radial motion, it leads to a wide range of distance estimates.

An independent distance estimate by Blair et al. (1999) combined the proper motion of a single filament with a shock speed obtained from spectroscopic analysis and fits to shock models. They derived a distance of 440 pc with a range of 340–570 pc. Their method assumed that $P_{\text{CR}}/P_G$ is zero, and a larger value would imply a higher shock speed and therefore a larger distance. This proper motion had a relatively large uncertainty because of the possible motions of the two reference stars. In a revised paper, Blair et al. (2005) derived a distance of 540 pc with a range of 460–640 pc from two epochs of HST Hα data for the same filaments.

The most solid limit on the distance to the Cygnus Loop comes from Blair et al. (2009). They used FUSE to observe a subdwarf OB (sdOB) background star and found strong high-velocity O vi absorption lines matching the O vi emission in the adjacent nebula. A fit to the FUSE spectrum provided the temperature and surface gravity of the star, indicating a distance of 57 ± 61 pc. The upper end of this range, 637 pc, should be a firm upper limit to the distance of the Cygnus Loop. Distances to sdOB stars are generally difficult to determine, but the spectral fits should give an accurate temperature. The uncertainty in the surface gravity probably dominates the 10% uncertainty in the distance.

3.5. Analyses of Other Balmer Line Shocks in the Cygnus Loop

Several of the Balmer line shocks at the periphery of the Cygnus Loop have been studied previously. The shock observed by Blair et al. (1999, 2005) has been observed extensively at optical and UV wavelengths (e.g., Raymond et al. 1983; Fesen & Itoh 1985; Long et al. 1992; Hester et al. 1994). We do not include it here (except to check our proper-motion measurements; Section 3.1.2) because it is too slow to produce X-ray emission. However, it fits in with our analysis in that the shock speed is estimated to be 150–190 km s$^{-1}$ and the proper motion is around two thirds the typical values we measure for the X-ray producing shocks.

The filament corresponding to our positions 15 and 16 was studied by Raymond et al. (1980) and Treffers (1981), who measured an Hα line width corresponding to a shock speed faster than 170 km s$^{-1}$. The filament corresponding to our positions 17 and 18 was discussed by Fesen et al. (1992) and Graham et al. (1995). The latter paper finds that the Balmer line filament in the region we observed is indeed the blast wave, rather than part of the shock structure refracted around the dense cloud just to the north.

Detailed studies of a position in the northeast have been made by Ghavamian et al. (2001) and Raymond et al. (2003). We have not included this exact region because two filaments overlap near there, but it lies between our regions 5 and 6. Ghavamian et al. (2001) obtained Hα and Hβ profiles and found nearly equal proton and electron temperatures ($T_p/T_e > 0.7$) and a shock speed of 235–395 km s$^{-1}$. Raymond et al. (2003) combined those results with UV spectra from FUSE and the Hopkins Ultraviolet Telescope.

4. COSMIC RAY TO GAS PRESSURE

The proper motion and temperature measurements described above, combined with a distance to the Cygnus Loop, allow calculation of the upper limit to the cosmic ray to gas pressure ratio downstream.

Taking the perspective of the shock front, momentum conservation applies to the pre- and post-shocked gas:

$$\rho \frac{\partial v}{\partial t} + \rho (v \cdot \nabla)v + \nabla p + \rho \nabla \phi = 0.$$

Assuming a steady state solution exists, ignoring the gravitational force term resulting from a field, $\phi$, and applying the continuity equation $\rho v = \text{constant}$, the momentum equation becomes

$$\rho v \frac{dv}{dx} + \frac{dP}{dx} = \frac{d}{dx}(P + \rho v^2) = 0.$$

This translates into a statement of constant momentum flux across the shock, allowing us to equate pressure terms

$$P_1 + \frac{B_1^2}{8\pi} + \rho_1 v_1^2 = P_{\text{CR}} + P_G + \frac{B_2^2}{8\pi} + \rho_2 v_2^2,$$

where $v_s$ is shock speed, $\rho$ is density, $P_{\text{CR}}$ is cosmic ray pressure originating in a dissipative shock environment, $P_G$ is downstream gas pressure, $B^2/8\pi$ is magnetic pressure, and the subscripts 1 and 2 represent conditions in the pre- and post-shock regions, respectively. We assume the ram and downstream pressures dominate, neglecting the ambient gas pressure and interstellar magnetic field. Assuming the case of a strong shock with adiabatic exponent $\gamma = \frac{5}{3}$ where $n_2/n_1 = 4$ and $v_2 = \frac{1}{2}v_s$, along with the equations of state $\rho_1 = n_1 m$ and $P_G = n_2 k T_2$, we derive

$$1 + \frac{P_{\text{CR}}}{P_G} = \frac{3mv^2}{16k T_2} = \frac{3m \mu^2 d^2}{16k T_2 \Delta^2},$$

where $T_2$ is the mean post-shock temperature. We assume ionization equilibrium exists, and that $T_2 = T_e = T_i$ (Ghavamian et al. 2001). We calculate shock velocities assuming only a tangential component, $v_s = v_t = \frac{d}{\Delta t}$, where $\Delta t$ is the angular propagation across the sky over a particular timescale (i.e., proper motion) and $d$ is distance to the Cygnus Loop. Adopting cosmic abundances with $n(\text{He})/n(\text{H}) = 0.098$ (Anders & Grevesse 1989), the mean mass per particle behind the shock, $m$, is determined by dividing the weighted molar mass per nucleus by the average number of particles per nucleus. The cosmic ray to gas pressure ratios presented in this paper are computed according...
to the equation derived above. We note that the compression factor of 4 may be an underestimate if cosmic ray pressure significantly impacts the gas dynamics, decreasing the post-shock flow speed relative to the shock, but as will be seen, we are primarily interested in low-efficiency shocks. We neglect line of sight velocity components in our calculations, assuming that the shock velocity is mostly perpendicular to the line of sight. We note that the appearance of multiple propagating shock layers is an artifact of our two-dimensional perspective. Instead, the complicated three-dimensional structure of the Cygnus Loop is wavy, warped, and sheet like (Raymond et al. 2003).

Cosmic ray to gas pressure ratios were calculated by combining proper motion and temperature measurements with an adopted distance of 576 ± 61 pc, obtained from a distance upper limit to a background sdOB star (Blair et al. 2009).

Note that the density has dropped out of the equations. The results we present here do not depend upon the ambient density, which is not very well known.

Table 2 lists best-fit values and upper limits of \( P_{\text{CR}}/P_G \) for all 18 filaments calculated independently with the apec and raymond ionization equilibrium temperature fits. To obtain conservative upper limits, we have used the upper limits to the shock speed \( v_s \) from Table 2 based on upper limits to the proper motions and the upper limit to the distance of 637 pc (Blair et al. 2009). We find several negative values for \( P_{\text{CR}}/P_G \). This result is unphysical and requires further investigation. For all instances of negative pressure ratios, we set \( P_{\text{CR}}/P_G \) to zero and derive a minimum distance estimate to the Cygnus Loop based on our proper motion and temperature uncertainties.

5. DISCUSSION

Inspection of the derived cosmic ray to gas pressure equation emphasizes the importance of constraining proper motion, distance, and temperature to infer tight upper limits on \( P_{\text{CR}}/P_G \). \( P_{\text{CR}}/P_G \) scales with the square of the shock speed, given by the product of proper motion and distance. In general, the upper limits indicate a small value for the ratio, and in some cases it is formally negative.

In the context of the discussions of the uncertainties given above, it is clear that the proper-motion measurements cannot account for the unphysical values of \( P_{\text{CR}}/P_G \). Most distance estimates are significantly smaller than the 637 pc we have adopted as the nominal upper limit, and it seems like a strain to make the distance large enough (~1 kpc) to make all the upper limits to \( P_{\text{CR}}/P_G \) positive. However, it may be possible given the general uncertainties in sdOB star distances.

Therefore, we conclude that the heart of uncertainty likely lies in post-shock temperature measurements and electron–ion thermal equilibration assumptions. Assuming ionization equilibrium and that shock velocity measurements are reasonably accurate, we require lower post-shock electron temperatures than measured from our ROSAT PSPC X-ray spectral fits. The fits based on the Raymond & Smith (1977) code give temperatures about 10% lower than those using APEC, but that is several times too small to explain the discrepancy.

5.1. Heating by Thermal Conduction

There is another possible way out of the discrepancy. We have assumed that \( T_e = T_i \) behind the shock, and it is possible that \( T_e > T_i \). However, such behavior is not seen in shocks in the interplanetary medium, and there is no obvious physical reason for such electron heating in the shock. Ghavamian et al. (2007) describe a wave heating mechanism that would produce particle temperatures somewhat higher than observed here, but \( T_p \) from Ghavamian et al. (2001) and a higher \( T_e \) would then require a large value of \( v_s \).

An interesting alternative is electron heating by thermal conduction from gas farther behind the shock. A number of papers have explored the global structure of SNRs with thermal conduction (e.g., Slavin & Cox 1992; Cox et al. 1999; Shelton et al. 1999). We can obtain an observational estimate from X-ray observations. Nemes et al. (2008) show the variation of \( T_e \) with radius in the northeastern Cygnus Loop based on XMM spectra, with a gradient of 0.05 keV over a distance of 0.07 times the shock radius, or \( \Delta T_e / \Delta R = 1.8 \times 10^{-13} \text{ K cm}^{-1} \). This implies a volumetric heating rate of about \( 3.4 \times 10^{-22} \text{ erg cm}^{-3} \text{ s}^{-1} \), which could heat the gas by about \( 3 \times 10^5 \text{ K} \) as it travels over the 100° region we analyze. Thus, the true post-shock temperature could be somewhat lower than the X-ray temperatures we measure by approximately the amount required for \( P_{\text{CR}} \) greater than zero. The above estimate requires a temperature gradient parallel to the magnetic field, so it could not be correct everywhere. However, only 7 of the 18 positions show \( P_{\text{CR}} \) nominally smaller than zero.

5.2. Shock Wave Deceleration Due to Pre-shock Density Increase

The shock wave velocity for each filament is assumed to be constant over the 39.1 year timespan of proper-motion analysis, implying a constant pre-shock density. However, the Cygnus Loop is believed to be interacting with a shell produced by the progenitor star (Hester & Cox 1986); thus, running into large, dense regions as observed in the west and northeast (Levenson et al. 2002). The possibility of recent shock wave deceleration due to an increase in pre-shock density, \( n_1 \), must be considered as an alternative explanation for unphysical (i.e., formally negative) \( P_{\text{CR}}/P_G \) values.

A reasonable approach to investigate the effect of pre-shock density on \( P_{\text{CR}}/P_G \) involves (1) calculating the shock speed required, \( v_0 \), to force \( P_{\text{CR}}/P_G = 0 \) and (2) then considering the feasibility of the density increase of the pre-shock medium implied by the “decelerated” shock speeds obtained from proper motions. To be conservative, only the seven positions with \( P_{\text{CR}} \) formally less than zero are considered. For each of these seven filaments, \( v_0 \) is calculated from the equation derived in Section 4 by setting \( P_{\text{CR}}/P_G \) to zero and using the \( T_{\text{ew}} \) values from Table 4. Following the same procedure in Section 4 gives an expression for the ratio of pre- to post-shock density:

\[
\frac{n_1}{n_2} = \frac{kT_2}{mv_0^2} + \frac{1}{16}.
\]

Assuming a strong shock and no deceleration from the initial shock speed, \( v_0 \), results in the well known relation \( n_1/n_2 = 1/4 \). We calculate pre-shock density fluctuations \( \Delta n_1/n_1 = (\Delta n_2/n_2 - 1/4)/1, \) where \( \Delta n_2/n_2 \) is calculated by inserting shock speeds derived from proper-motion measurements and assuming that post-shock density, \( n_2 \), remains constant. Table 5 lists shock speeds and pre-shock density fluctuations required for nonnegative \( P_{\text{CR}}/P_G \) values.

To explain the discrepancy of negative \( P_{\text{CR}}/P_G \) by rapid shock deceleration alone, density fluctuations of \( \sim 0.3 \) to 1.0 are required to account for \( P_{\text{CR}}/P_G \sim -0.3 \) to \( -0.6 \) (Table 5). Raymond (2003) studied the amplitudes and wavelengths of nonradiative shock ripples in the northern Cygnus Loop

---

No. 1, 2009  CYGNUS LOOP  337
Table 5

| Filament ID | $T_{\text{low}}$ (eV) | $v_0$ (km s$^{-1}$) | $v_{\text{max}}$ (km s$^{-1}$) | $\Delta n_1/n_1$ | $P_{\text{CR}}/P_{\text{G}}$ $\times$ 10$^{-6}$ |
|-------------|----------------------|---------------------|-------------------------------|-----------------|----------------------|
| 4           | 137                  | 340                 | 225                           | 0.96            | $-0.560$             |
| 5           | 136                  | 339                 | 278                           | 0.36            | $-0.325$             |
| 7           | 84.9                 | 268                 | 240                           | 0.18            | $-0.193$             |
| 8           | 148                  | 353                 | 274                           | 0.50            | $-0.397$             |
| 9           | 138                  | 341                 | 294                           | 0.26            | $-0.259$             |
| 15          | 107                  | 300                 | 272                           | 0.16            | $-0.182$             |
| 16          | 144                  | 348                 | 264                           | 0.56            | $-0.428$             |

Notes. Shock speed and pre-shock density fluctuations for seven filaments with $P_{\text{CR}}/P_{\text{G}}$ nominally less than zero, assuming a decelerating shock wave over the 39.1 year proper-motion analysis timespan. Initial shock speeds, $v_0$, are calculated by requiring $P_{\text{CR}}/P_{\text{G}} = 0$ and density fluctuations of the pre-shock medium, $\Delta n_1/n_1$, are calculated relative to $n_1/n_2$ obtained from $v_0$. The most conservative estimates of $P_{\text{CR}}/P_{\text{G}}$ are listed and show that density increases of the pre-shock medium up to $\sim$96% over $\sim$0.1 pc are required to explain negative $P_{\text{CR}}$ values by recent shock wave deceleration alone.

and found density fluctuations in the pre-shock medium of $\Delta n_1/n_1 \sim 0.2$ on 10$^{10}$ cm scales. Therefore, density inhomogeneities can only account for $P_{\text{CR}}/P_{\text{G}} \sim -0.2$ and should provide a scatter about zero rather than consistently negative values across the broad region we examine. While rapid deceleration is a possibility, it would be remarkably coincidental for large enough density increases to occur over most of the northern Cygnus Loop simultaneously over a scale of $\sim$0.1 pc, especially since this region is not a sphere to within 0.1 pc. This explanation would also require the shell interaction scenario to apply to the northern regions, rather than just to the regions of bright optical and X-ray emission.

6. SUMMARY

Constraining $P_{\text{CR}}/P_{\text{G}}$ in supernova shocks is important for assessing the efficiency of energy dissipation by the SNR into accelerating cosmic rays. We combine measured proper motions with temperatures derived from X-ray spectra and an upper limit on the distance to obtain upper limits to $P_{\text{CR}}/P_{\text{G}}$. We measured proper motions and post-shock temperatures of 18 faint nonradiative Hz filaments in the Cygnus Loop. Proper-motion measurements of filaments based on image matching and correlation techniques yield continuous results over extended shock regions. Post-shock electron temperatures from X-ray fits are higher than expected if the current 576 $\pm$ 61 pc distance measurement to the Cygnus Loop is accurate.

We conclude that (1) $P_{\text{CR}}/P_{\text{G}}$ is small, (2) the distance to the Cygnus Loop must be close to or even larger than the upper limit given by the apparent distance to a star that lies behind the SNR, (3) uncertainties in the temperature derived from X-ray spectra might dominate the uncertainties in the analysis, and (4) thermal conduction from hotter interior gas could alter the immediate post-shock temperature enough to account for the observations.

Future work will focus on constraining post-shock temperature and investigating the validity of ionization equilibrium on a more global scale along the northeastern Cygnus Loop, and placing tighter constraints on the distance to the Cygnus Loop.

This work is supported in part by the National Science Foundation Research Experiences for Undergraduates (REU) and Department of Defense Awards to Stimulate and Support Undergraduate Research Experiences (ASSURE) programs under grants 0754568 and by the Smithsonian Institution.

We acknowledge generous data policies of the Space Telescope Science Institute, for digitizing and archiving the Palomar Observatory Sky Surveys, and the High Energy Astrophysics Space Astronomy Archival Research Center (HEASARC) at the NASA/Goddard Space Flight Center, for making the ROSAT data available. The Digitized Sky Survey was produced at the Space Telescope Science Institute under US Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions. R.J.E. acknowledges support from NASA contract NAS8-03060 (the Chandra X-ray Center) to the Smithsonian Astrophysical Observatory.
Raymond, J. C., & Smith, B. W. 1977, ApJS, 35, 419
Sakhibov, F. H., & Smirnov, M. A. 1983, SvA, 27, 395
Shelton, R. L., Cox, D. P., Maciejewski, W., Smith, R. K., Plewa, T., Pawl, A., & Różyczka, M. 1999, ApJ, 524, 192
Shull, P. I., & Hippelein, H. H. 1991, ApJ, 383, 714
Slavin, J. D., & Cox, D. P. 1992, ApJ, 392, 131
Smith, R. C., Raymond, J. C., & Laming, J. M. 1994, ApJ, 420, 286
Smith, R. K., Brickhouse, N. S., Liedahl, D. A., & Raymond, J. C. 2001, ApJ, 556, L91
Treffers, R. R. 1981, ApJ, 250, 213
Tsunemi, H., Katsuda, S., Nemes, N., & Miller, E. D. 2007, ApJ, 671, 1717
Turner, T. J. 1996, OGIP Memo OGIP/94-010
van Adelsberg, M., Heng, K., McCray, R., & Raymond, J. C. 2008, ApJ, 689, 1089
Warren, J. S., et al. 2005, ApJ, 634, 376