Shock Speed, Cosmic Ray Pressure, and Gas Temperature in the Cygnus Loop

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Abstract:

We have measured proper motions (from two epochs of Palomar Observatory Sky Survey plates) and post-shock temperatures (from ROSAT pointed observations) for 18 positions around the forward shock in the Cygnus Loop. The differences between shock velocity derived from the two methods constrain the efficiency of cosmic ray acceleration.

Our measurements show a ratio of cosmic ray pressure to gas pressure consistent with zero. In some cases, our formal upper limits are negative. This suggests that the distance to the Cygnus Loop may be underestimated, the electron temperatures are lower than measured with ROSAT, or an additional source of heating for the electrons is present.

The Idea

- We measure the proper motion for the Balmer dominated filaments at a number of points (as marked) around the rim of the Cygnus loop.

- This proper motion combined with a distance estimate gives the shock speed.

- The electron temperature of the post-shock gas is measured by fitting the ROSAT x-ray spectrum.

$$\frac{P_{CR}}{P_G} = \frac{3mv_s^2}{16kT_s} - 1$$

- Any leftover energy can go into accelerating cosmic rays.

- **But...** the electrons are too hot for the measured proper motion, given the best available distance.

- As can be seen in Figure 3, the formal limits on this pressure ratio are often negative.

Proper Motions

- The Palomar Observatory Sky Survey (POSS) took red plates of the Cygnus Loop region at two epochs, separated by about 39.1 years. The H–α filaments are clearly visible, and obviously moved.

- The data were rotated, and regions free of stars were selected (see Figure 1 for filament 7). Autocorrelations were performed, and highly significant proper motions were derived.

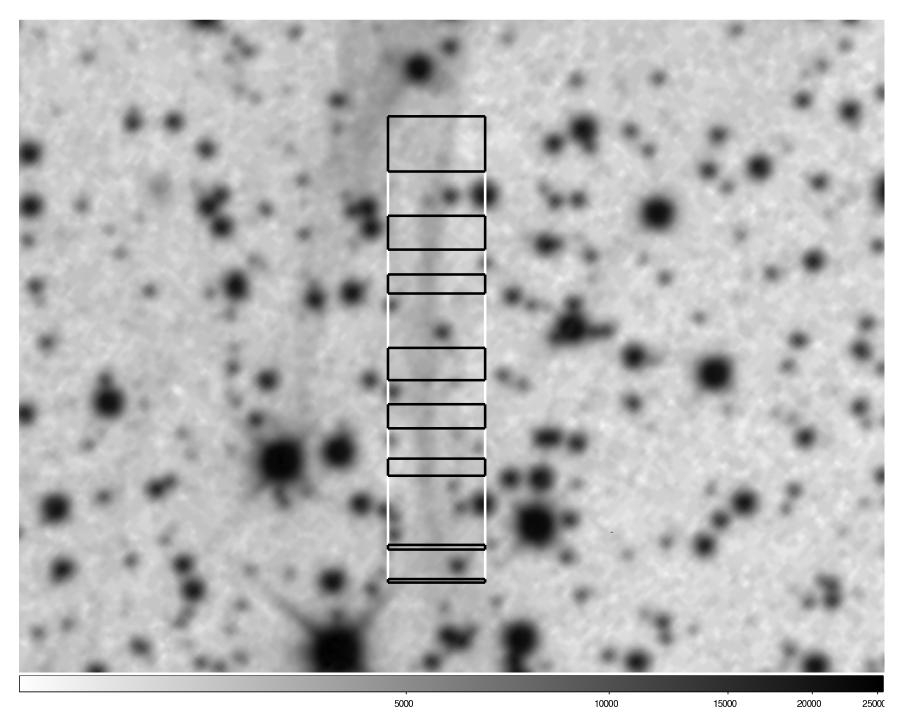- Errors were estimated using bootstrap resampling methods.

Figure 1: Region selection process for H$-\alpha$ Filament 7. Note exclusion of the stars.

Post-shock Temperatures

- Data from ROSAT PSPC pointed observations were extracted for regions from $25''$ to $100''$ behind each filament.

- These were fitted to a variety of one- and two-temperature models. A low temperature component with $kT \sim 135$ eV is ubiquitous. Similar results are found from fitting the observations of the forward shock regions with Suzaku, XMM, and Chandra.

Distance

- We take our distance estimate from Blair, Sankrit, Torres, Chayer and Danforth, 2009, ApJ, 692, 335.

- Blair et al. observed subdwarf OB (sdOB) star KPD 2055+3111 with FUSE and found a broad $\lambda1032$ O VI absorption line in its spectrum. This demonstrates that the star is behind the Cygnus Loop.

- From optical spectroscopy, the distance to the star is 576 ± 61 pc. We take this to be an upper limit to the distance to the Cygnus Loop.

Conclusions

- Combining fitted temperatures with shock velocities from proper motions and the distance of Blair et al (derived from high velocity UV absorption lines toward a subdwarf O star behind the remnant), we find upper limits to the P_{CR}/P_G ratio which are often negative.

- It seems clear from these results that P_{CR}/P_G is small, and that the forward shock in the Cygnus Loop is not a highly efficient accelerator of cosmic rays.

- Clearly negative values of P_{CR}/P_G are unphysical.

- Possible outs:

  – Electron temperatures are higher than we measure with ROSAT (but Suzaku, Chandra, XMM get similar low temperature results)

  – Distance is larger; ~ 900 pc (but what about the Blair et al. sdOB star?)

  – Sharp density gradient (why all around the loop right now, when the loop is non-spherical?) Reflected shock (same objections).

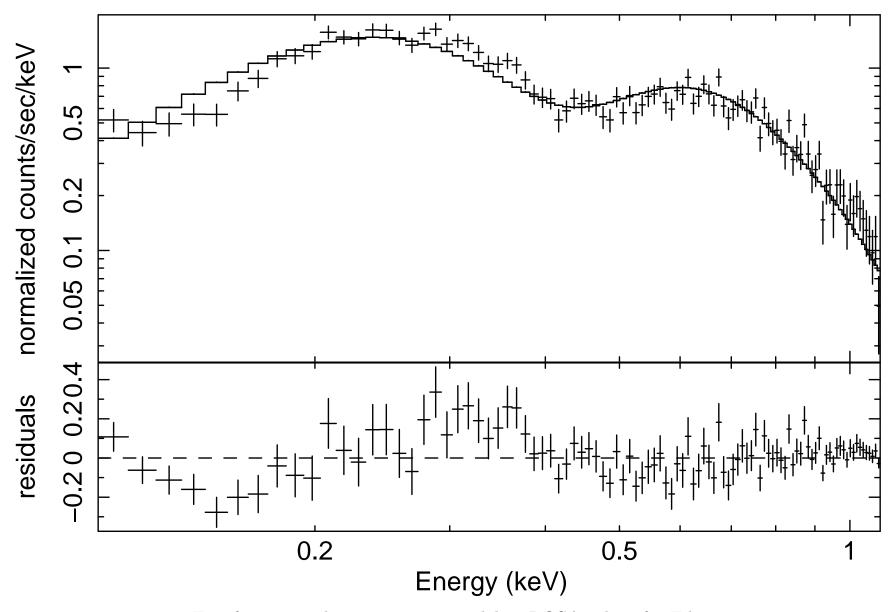 – Thermal conduction up to the shock front from the hot interior?

Figure 2: Fit of `apec` single-temperature model to ROSAT data for Filament 7.
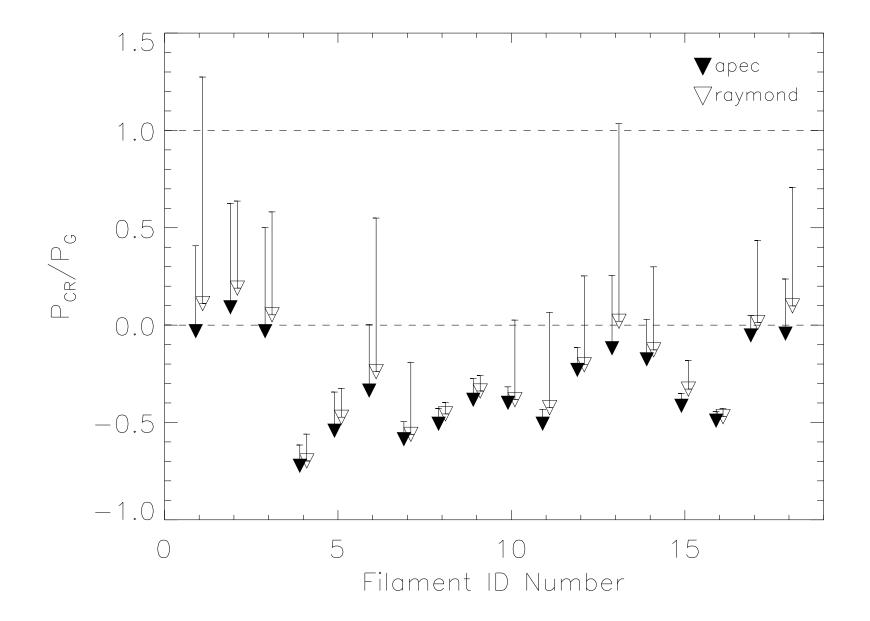
Figure 3: Upper limits to the cosmic ray to gas pressure ratio, given temperatures fit using `apec` and `raymond` models.

Table 1:

Proper Motion and P_{cr}/P_g Values for Selected Hα Filaments

Filament ID	α_{J2000}	δ_{J2000}	Proper Motion arcsec / 39.1 yr	v_{max} km s^{-1}	$(P_{CR}/P_G)_{\text{apec}}$	$(P_{CR}/P_G)^{MAX}_{\text{apec}}$	d^{MIN}_{apec} pc	$(P_{CR}/P_G)_{\text{raymond}}$	$(P_{CR}/P_G)^{MAX}_{\text{raymond}}$	d^{MIN}_{raymond} pc
1	20 51 23.9	32 24 22.5	$5\farcs1 \pm 0\farcs2$	403	-0.032	0.408	537	0.111	1.274	422
2	20 51 29.9	32 24 21.8	$5\farcs4 \pm 0\farcs2$	433	0.091	0.625	500	0.190	0.637	498
3	20 51 38.6	32 24 14.5	$5\farcs2 \pm 0\farcs2$	416	-0.032	0.501	520	0.053	0.582	507
4	20 54 13.1	32 21 14.0	$2\farcs7 \pm 0\farcs2$	225	-0.723	-0.616	1028	-0.698	-0.560	960
5	20 54 26.2	32 19 36.5	$3\farcs4 \pm 0\farcs2$	278	-0.543	-0.344	786	-0.473	-0.325	775
6	20 54 43.4	32 16 04.0	$4\farcs1 \pm 0\farcs2$	333	-0.337	-0.004	638	-0.239	0.550	512
7	20 55 06.3	32 10 03.8	$3\farcs0 \pm 0\farcs1$	240	-0.587	-0.496	897	-0.561	-0.193	709
8	20 55 14.7	32 07 38.9	$3\farcs4 \pm 0\farcs1$	274	-0.507	-0.428	843	-0.456	-0.397	821
9	20 55 18.9	32 06 58.0	$3\farcs7 \pm 0\farcs1$	294	-0.384	-0.275	748	-0.338	-0.259	740
10	20 55 34.6	32 01 40.2	$3\farcs5 \pm 0\farcs1$	279	-0.400	-0.317	771	-0.383	0.026	629
11	20 55 44.9	31 59 43.8	$3\farcs1 \pm 0\farcs2$	254	-0.507	-0.432	845	-0.424	0.066	617
12	20 55 51.8	31 57 34.8	$4\farcs0 \pm 0\farcs2$	319	-0.231	-0.115	677	-0.203	0.253	569
13	20 55 56.5	31 55 55.1	$4\farcs2 \pm 0\farcs7$	375	-0.120	0.256	568	0.020	1.034	447
14	20 57 20.2	31 37 32.4	$4\farcs3 \pm 0\farcs1$	342	-0.176	0.030	628	-0.127	0.299	559
15	20 45 11.9	31 03 50.0	$3\farcs4 \pm 0\farcs1$	272	-0.415	-0.351	791	-0.329	-0.182	704
16	20 45 15.3	31 01 41.4	$3\farcs3 \pm 0\farcs1$	264	-0.492	-0.443	854	-0.470	-0.428	842
17	20 56 37.4	30 08 34.4	$4\farcs5 \pm 0\farcs1$	358	-0.054	0.049	622	0.013	0.434	532
18	20 56 34.8	30 06 27.8	$4\farcs8 \pm 0\farcs1$	379	-0.044	0.237	573	0.099	0.707	...

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 $\leq 0\farcs1$ 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 $P_{CR}/P_G = 0$ 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:

X-ray Spectral Fit Parameters with the `apec` Model

Filament ID	T_{cos} eV	$N_{H,cos}$ 10^{20} cm^{-2}	$(\chi^2/\nu)_{cos}$	T_{dep} eV	$(\chi^2/\nu)_{dep}$	T_{low} eV	T_{high} eV	$(\chi^2/\nu)_{double}$
1	187^{+6}_{-6}	$2.4^{+0.2}_{-0.2}$	1.65	162^{+10}_{-7}	3.37	137	536	1.13
2	192^{+7}_{-6}	$2.4^{+0.2}_{-0.2}$	1.80	198^{+10}_{-9}	3.01	137	602	1.28
3	198^{+7}_{-6}	$2.5^{+0.2}_{-0.2}$	1.44	230^{+10}_{-10}	2.47	137	336	1.16
4	190^{+6}_{-6}	$2.3^{+0.2}_{-0.2}$	0.96	194^{+9}_{-8}	1.86	157	454	0.85
5	181^{+5}_{-4}	$2.5^{+0.2}_{-0.2}$	1.48	159^{+8}_{-6}	3.21	140	605	1.06
6	179^{+4}_{-2}	$2.1^{+0.1}_{-0.1}$	2.33	151	5.75	132	380	1.60
7	154^{+5}_{-4}	$2.6^{+0.2}_{-0.2}$	2.22	119	5.95	136	541	1.53
8	170^{+12}_{-4}	1.2	1.26	118^{+4}_{-4}	3.44	156	661	1.06
9	159^{+6}_{-5}	$1.7^{+0.2}_{-0.2}$	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^{+8}_{-7}	$1.8^{+0.3}_{-0.3}$	1.48	115^{+7}_{-4}	3.14	135	727	0.89
15	140^{+3}_{-5}	$2.1^{+0.2}_{-0.2}$	2.81	80.8	5.24	135	812	2.29
16	150^{+4}_{-4}	$2.4^{+0.1}_{-0.1}$	1.02	86.8	1.91	148	692	1.03
17	152^{+13}_{-9}	$4.2^{+0.6}_{-0.7}$	1.19	146^{+9}_{-7}	1.91	145	159	1.24
18	169^{+11}_{-20}	$3.8^{1.1}_{-0.5}$	1.32	155^{+23}_{-10}	1.88	138	633	1.24

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 `phabs` $\times$ `apec` with abundances fixed to cosmic. The subscript 'dep' refers to single-temperature model fits `phabs` $\times$ `vapec` with depleted abundances fixed to 10% cosmic. The subscript 'double' refers to double-temperature model fits `phabs` $\times$ `(apec+apec)` with abundances fixed to cosmic. We allowed N_H to vary from an initial value of 1.5×10^{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 χ^2 statistics.