Applying Models With Reverse Shocks To Galactic Supernova Remnants In The VGPS Survey

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ABSTRACT

We apply SNR interior structure models to Galactic supernova remnants (SNR) in the VGPS survey to obtain properties of the Galactic SNR population. The models include the evolution of SNR interior structure for both forward and reverse shocks, and calculate forward and reverse shock X-ray emission measures at any time. By applying the models to SNRs with measure X-ray spectra, we obtain estimates of explosion energy, age and ejecta mass for a set of 15 SNRs.

INTRODUCTION

The study of supernova remnants (SNRs) is of great interest in astrophysics and provides valuable information relevant to stellar evolution, the evolution of the Galaxy, and its interstellar medium (ISM). SNRs are the dominant source of kinetic energy input into the ISM (Cox 2005) and thus measuring SNR energetics is critical to understanding the structure of the ISM.

Only a small fraction of the ~300 observed SNRs in our Galaxy have previously been characterized well enough to determine their evolutionary state, including explosion type, explosion energy, and age. In order to characterize SNRs, we have developed a set of analytical SNR models for spherically symmetric SNRs (Leahy & Williams 2017, Leahy, Wang and Lawton 2019). The set of models include a wide set of models constructed previously by other authors. We carried out the additional steps of consistently joining different stages of evolution, calculating forward and reverse shock mean temperatures and emission measures, and including electron heating. The resulting models facilitate the process of using different constraints from observations to estimate SNR physical properties of interest.

SNR EVOLUTION

The various stages of evolution of an SNR include, in order, the ejecta-dominated stage (ED), the adiabatic (or Sedov–Taylor) stage (ST), and radiative stages. The radiative stages are usually divided into the earlier pressure-driven snowplow (PDS) stage and later the momentum-conserving shell (MCS) stage. In addition to these phases, there are the transitions between stages, which are ED to ST, ST to PDS, and PDS to MCS, respectively. The ED to ST stage is particularly important because the SNR is still bright in X-rays and radio, and it is long-lived enough that a significant number of Galactic SNRs could be in this phase. The end of the life of the SNR is usually taken to be when the SNR merges with the ISM.

ADOPTED MODEL FOR SNRS

The model for SNR evolution that we construct is partly based on the Truelove & McKee (1999) analytic solutions, with additional features (Leahy & Williams, 2017, Leahy, Wang and Lawton 2019).

1. We calculate the emission measure (EM) and emission measure-weighted temperature during the transition from the ED phase to ST phase.
2. The inverse problem is solved, which takes as input the SNR observed properties and determines the initial properties of the SNR.

SNR SAMPLE

15 SNRs in the VLA Galactic Plane Survey (VGPS).

- Distances estimated using HI and ^{13}CO data to obtain SNR radius.
- EM and EM-weighted temperature comes from the X-ray studies.

SNR Model Results

SNR	Model Type	s	n	M_{ej} ($M_\odot$)	Age (yr)	Energy (10^{51} erg)	n_0 (s = 0) (cm^{-3})	ρ_s (s = 2) ($M_\odot s$/ km yr)
G18.1-0.1	fs	0	7	1.4	5400	0.189	0.92	n/a
G21.5-0.9	rs	0	9	5	470	0.56	1.01	n/a
G21.8-0.6	fs	0	7	1.4	9700	0.33	0.078	n/a
G27.4+0.0	fs	0	12	10	2500	0.32	1.08	n/a
G28.6-0.1	fs	0	7	1.4	14700	0.95	0.028	n/a
G29.7-0.3	rs	0	9	5	890	0.46	0.43	n/a
G31.9+0.0	rs	0	9	10	9000	0.39	4.5	n/a
	WL	n/a	n/a	n/a	8700	0.39	2.6	n/a
G32.8-0.1	fs	0	7	1.4	7500	0.067	0.018	n/a
G33.6+0.1	fs	2	7	20	780	2.9	n/a	6.3×10^{-8}
G34.7-0.4	fs	0	7	5	9100	2.2	1.52	n/a
	WL	n/a	n/a	n/a	9200	2.2	0.86	n/a
G39.2-0.3	fs	0	7	5	6200	0.24	0.32	n/a
G41.1-0.3	fs	2	7	1.4	1300	0.95	n/a	9.5×10^{-7}
G43.3-0.2	fs	0	7	1.4	3250	1.69	1.17	n/a
	WL	n/a	n/a	n/a	3100	1.82	0.66	n/a
G49.2-0.7	fs	0	9	10	16000	0.76	0.021	n/a

Model type: fs is the forward shock model; rs is the reverse shock model; WL is the model of White & Long (1991) with Coulomb equilibration added.

ESTIMATED SNR POPULATION PROPERTIES

Figure1: The 1 per 300 yr line fits well the SNRs with the smallest 3 ages and the 1 per 700 yr line fits approximately the SNRs with the 10 lowest ages (increasing incompleteness of the sample for older SNRs)

Figure 2: Cumulative distribution of explosion energies is not consistent with uniform or Gaussian distributions, but is consistent with a log-normal distribution.

Figure3: The cumulative distribution of ISM for the 13 of the 15 SNRs with a derived ISM density is consistent with a log-normal distribution.

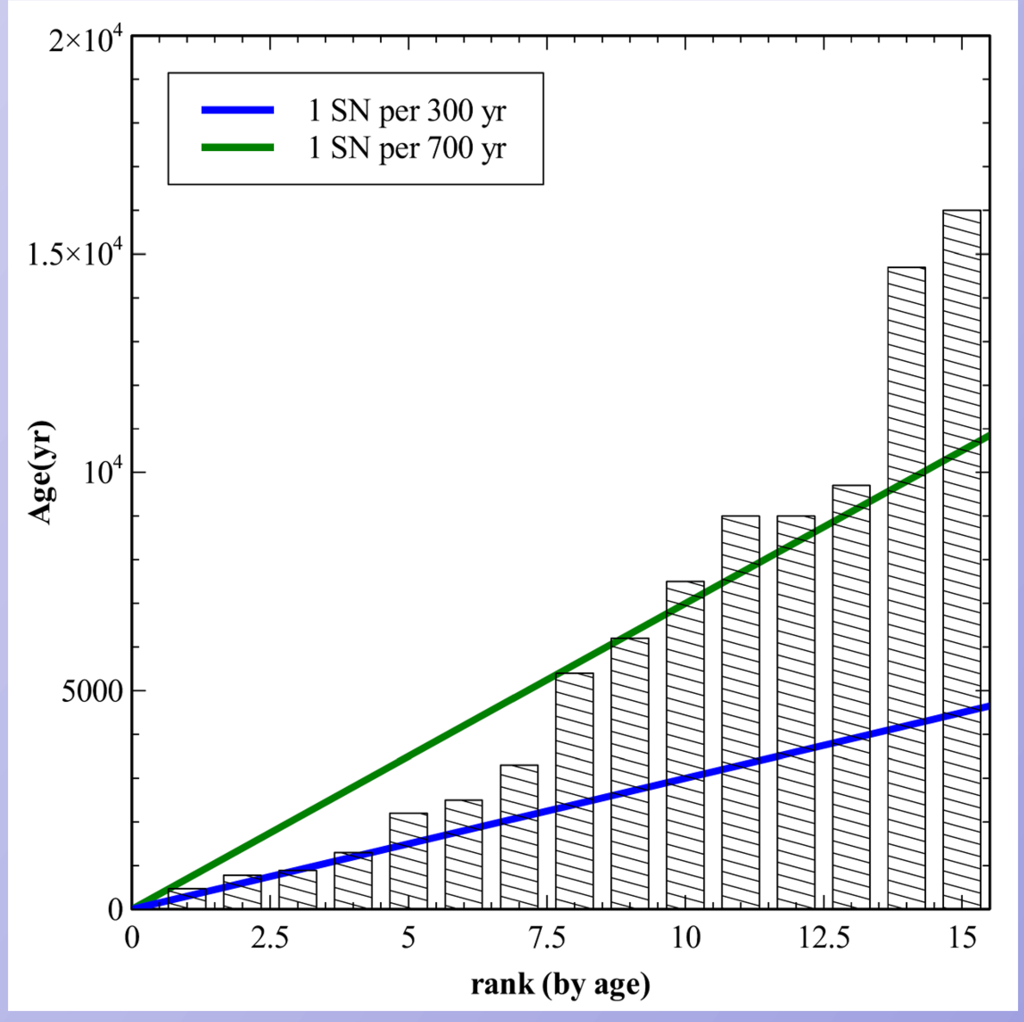

Figure1: Cumulative distribution of model ages and fit lines for birth rate of 1 per 300 yr and 1 per 700 yr.

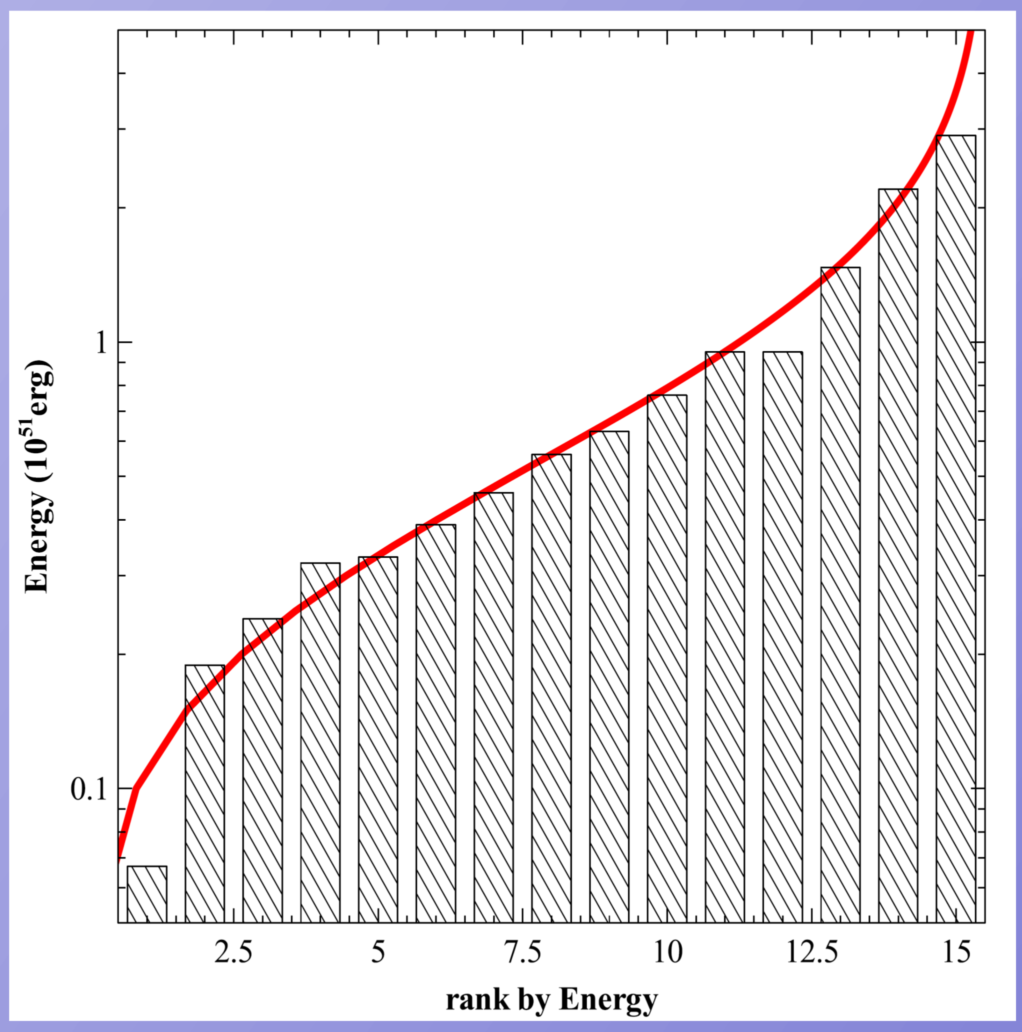

Figure 2: Cumulative distribution of model explosion energies of the 15 SNRs and fit line for a log-normal distribution of explosion energies with mean explosion energy of $E_0 = 5.4 \times 10^{50}$ erg and variance in $\log(E_0)$ of 0.45.

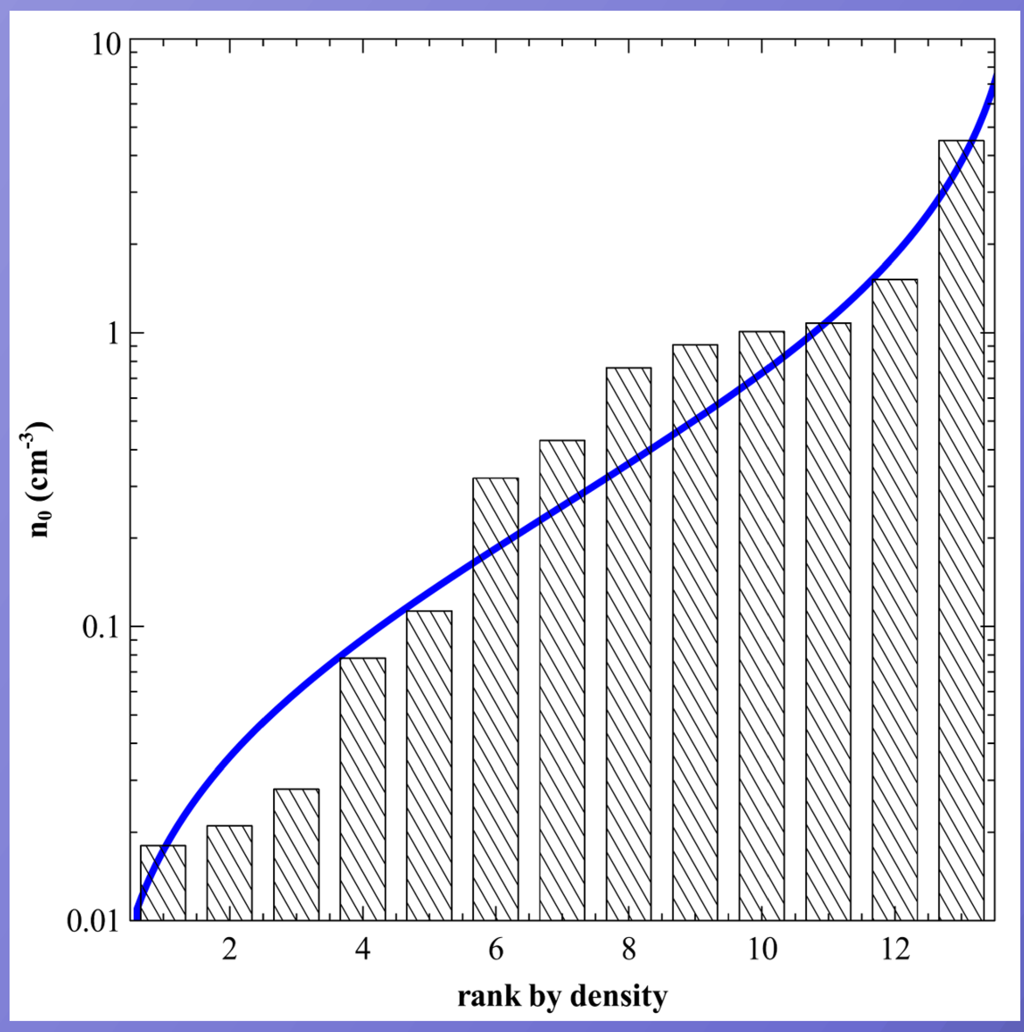

Figure 3: Cumulative distribution of model ISM densities and fit line for a log-normal distribution of ISM densities with mean density of $n_0 = 0.26$ cm^{-3}, and variance in $\log(n_0)$ of 0.80.

CONCLUSION

Distances to Galactic SNRs have improved significantly, allowing determination of radii and enabling the application of SNR models.

- We extended spherically symmetric SNR evolution models to include effects of ejecta mass and emission from shocked ejecta.
- The models are applied to estimate SNR parameters for our sample of SNRs from the inner Galaxy.
- We examined the distributions of the parameters to determine properties of the Galactic SNR population in the inner Galaxy.
- The estimated birth rate of SNRs and found it to be consistent with estimates of the overall Galactic SNR birth.
- We find that the energies and ISM densities of SNRs can be well fit with log-normal distributions.
- The distribution of explosion energies is very similar to that for SNRs in the Large Magellanic Cloud (LMC), suggesting a surprisingly close similarity in the population of SN explosions in the LMC and in the Galaxy.
- The ISM density distributions for Galactic and LMC SNRs have similar dispersion, but Galactic SNRs have a higher mean density by a factor ~2.5. A higher mean density is expected because our sample SNRs are selected from the inner Galaxy.

FUTURE WORK

We Intend to extend the study of SNRs to include all Galactic SNRs with measured distances and X-ray spectra. The goal is to significantly increase the sample size and better determine the intrinsic properties of SNRs.

References

- Cioffi, D. F., McKee, C. F., & Bertschinger, E. 1988, ApJ, 334, 252
- Cox, D. P. 2005, ARA&A, 43, 337
- Leahy, D. A. 2017, ApJ, 837, 36
- Leahy, D. A., & Ranasinghe, S. 2018, ApJ, 866, 9
- Leahy, D.A., Wang, Y., Lawton, B. 2019 arXiv 1902.08284
- Leahy, D. A., & Williams, J. E. 2017, AJ, 153, 239
- Truelove, J. K., & McKee, C. F. 1999, ApJS, 120, 299
- Vink, J. 2012, A&ARv, 20, 49
- White, R. L., & Long, K. S. 1991, ApJ, 373, 543