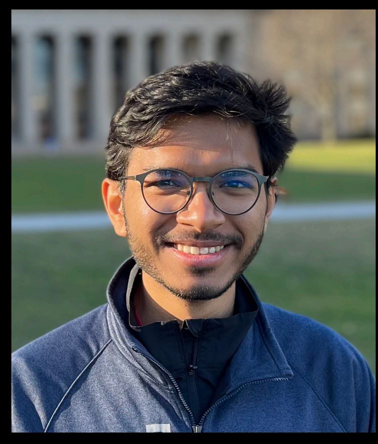
GREEN MONSTER
in Cassiopeia A investigated in X-rays



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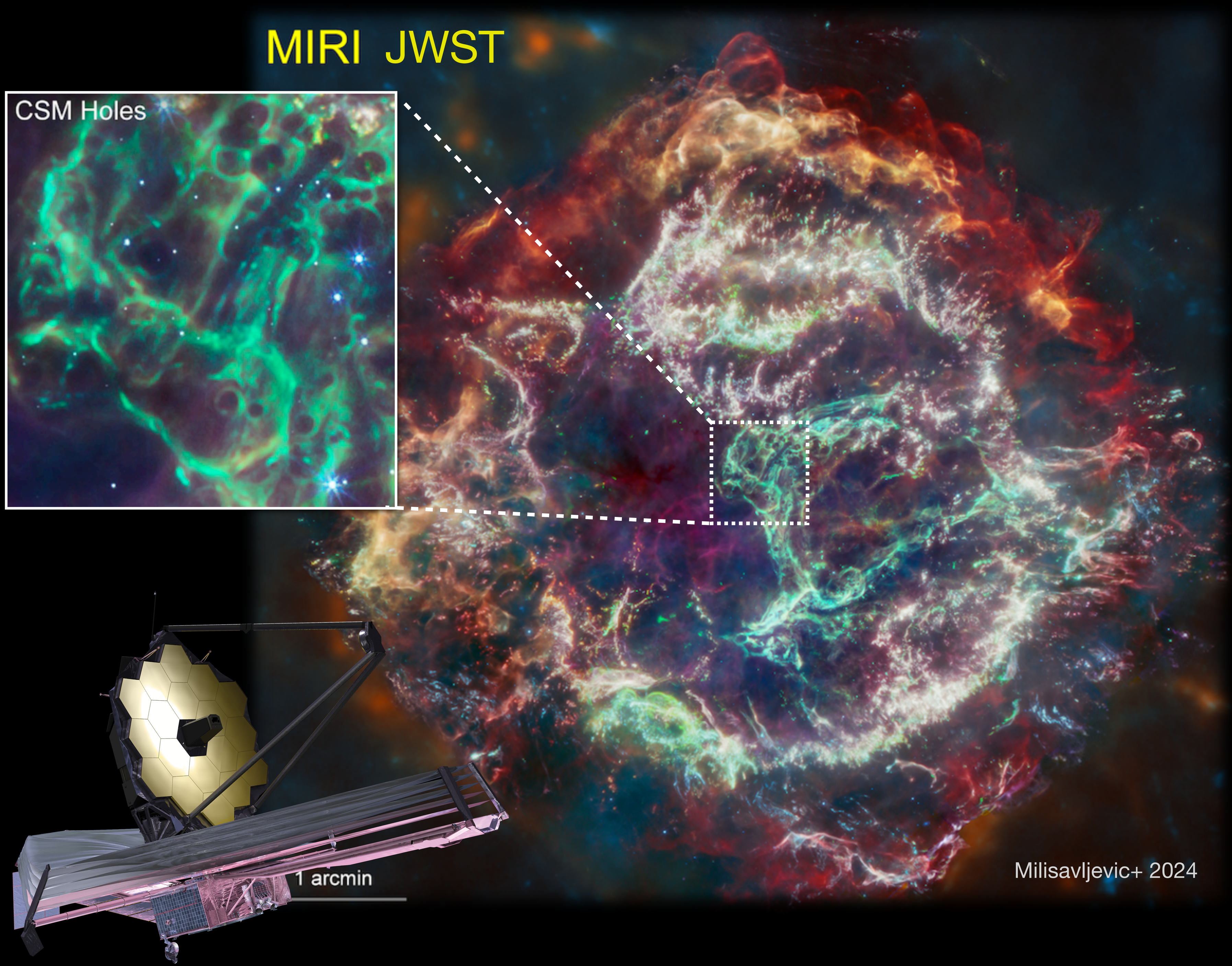
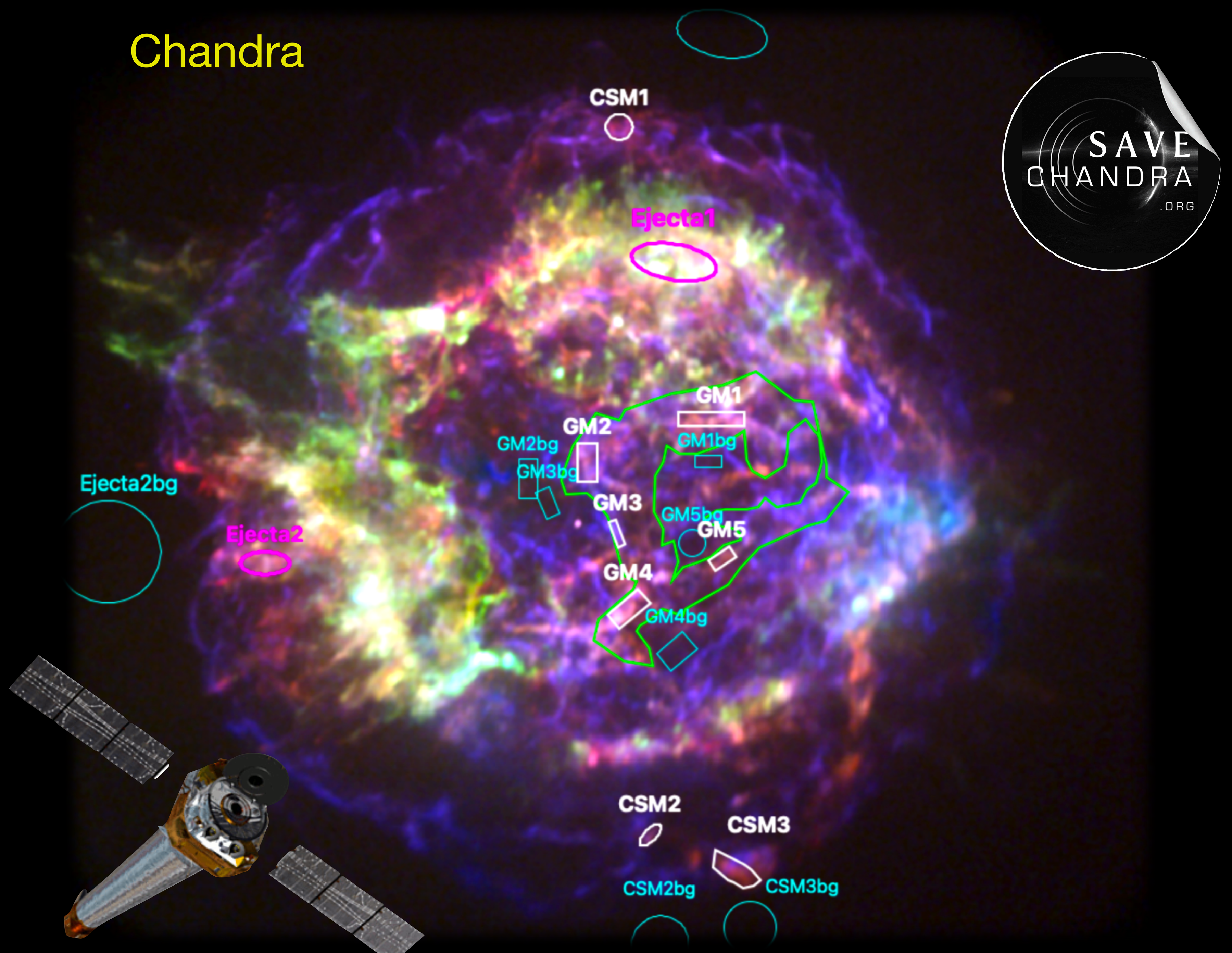
JWST/MIRI images of the core-collapse supernova remnant, Cassiopeia A (Cas A), revealed a large interior structure, referred to as the "Green Monster". Although its central location suggests an ejecta association, the infrared properties of the Green Monster hint at a circumstellar medium (CSM) origin. We investigate the filamentary X-ray structures associated with the Green Monster using archival data from the Chandra X-ray Observatory. The extracted spectra as well as a principal component analysis show that the Green Monster's emission properties are more similar to those of the shocked CSM than the ejecta. All the Green Monster associated spectra show a blueshift corresponding to a radial velocity of around $-2300\ \mathrm{km\,s^{-1}}$, suggesting that the structure is on the near side of Cas A. The ionization age is around $n_e t \approx 1.5 \times 10^{11}\ \mathrm{cm^{-3}s}$, which implies a pre-shock density of $\sim 12\ \mathrm{cm^{-3}}$, higher than previous estimates of the unshocked CSM. Both the relatively high density and relatively low radial velocity suggest a CSM structure that is denser than the rest of the CSM. This provides yet another piece of evidence that the CSM around Cas A's progenitor was not that of a smooth steady wind profile.





Evidence 1: Spectral Analysis

We used the archival Chandra 2004 VLP observation of Cas A (total exposure of 1 million sec). We extracted five spectra along the Green Monster associated filaments and three from various shocked CSM regions. Background spectra were obtained from faint nearby regions. We employed the Bayesian scheme, BXA, and performed a simultaneous fit to all combined GM, and combined CSM spectra. We fit a model consisting of a combination of a non-equilibrium ionization model (vpshock) and a power-law component, modified by Galactic absorption.

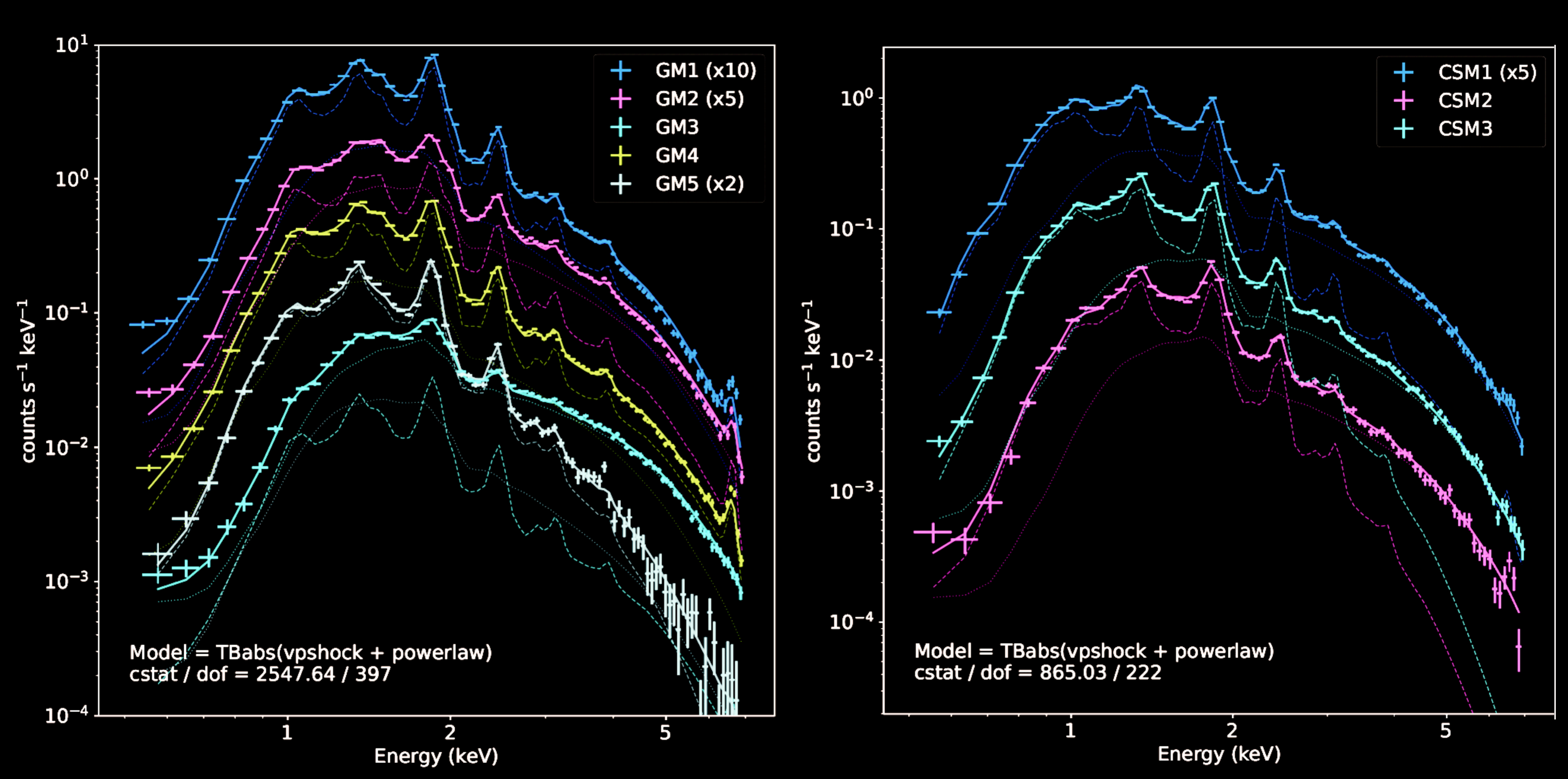


Fig 1: The figure shows the bayesian-based best-fit models to X-ray spectra from the GM and CSM regions. The dashed and dotted lines show the model contributions of the vpshock and the power-law components, respectively.

	Priors	GM 1	GM 2	GM 3	GM 4	GM 5	CSM 1	CSM 2	CSM 3
kT_e (keV)	0.1–5^c	$1.92^{+0.03}_{-0.03}$	$2.19^{+0.06}_{-0.06}$	$2.33^{+0.33}_{-0.33}$	$3.01^{+0.06}_{-0.06}$	$0.88^{+0.02}_{-0.02}$	$1.76^{+0.12}_{-0.12}$	$0.79^{+0.06}_{-0.06}$	$0.78^{+0.03}_{-0.03}$
$\tau_\mathrm{max}\,(10^{11}\mathrm{cm^{-3}s})$	0.05–8	$1.17^{+0.03}_{-0.03}$	$2.24^{+0.10}_{-0.10}$	$0.98^{+0.14}_{-0.12}$	$0.96^{+0.02}_{-0.02}$	$3.56^{+0.24}_{-0.22}$	$0.62^{+0.04}_{-0.04}$	$2.66^{+0.56}_{-0.46}$	$2.32^{+0.22}_{-0.20}$
$v_\mathrm{rad}\,(\mathrm{km\,s^{-1}})$	-3000–3000^c	$-2,400^{+3}_{-3}$	$-1,240^{+56}_{-56}$	$-2,886^{+163}_{-163}$	$-1,878^{+11}_{-11}$	$-2,314^{+26}_{-26}$	-61^{+48}_{-48}	$-1,453^{+212}_{-212}$	24^{+84}_{-84}
norm ^{a}	0.1–100	$3.76^{+0.13}_{-0.12}$	$1.63^{+0.05}_{-0.05}$	$0.19^{+0.02}_{-0.01}$	$2.60^{+0.08}_{-0.08}$	$1.19^{+0.04}_{-0.04}$	$0.56^{+0.07}_{-0.06}$	$0.61^{+0.08}_{-0.07}$	$2.14^{+0.20}_{-0.18}$
Γ	2.5–3.7^c	$3.69^{+0.01}_{-0.01}$	$2.95^{+0.01}_{-0.01}$	$2.56^{+0.02}_{-0.02}$	$3.70^{+0.01}_{-0.01}$	$3.69^{+0.03}_{-0.03}$	$2.89^{+0.03}_{-0.03}$	$2.98^{+0.07}_{-0.07}$	$2.93^{+0.05}_{-0.05}$
$N_\mathrm{H}\,(\mathrm{cm^{-2}})$	0.1–4^c	$1.86^{+0.01}_{-0.01}$	$1.72^{+0.01}_{-0.01}$	$2.15^{+0.02}_{-0.02}$	$1.77^{+0.01}_{-0.01}$	$2.04^{+0.01}_{-0.01}$	$1.35^{+0.02}_{-0.02}$	$2.20^{+0.03}_{-0.03}$	$1.82^{+0.02}_{-0.02}$
C-stat/bins		896.96 / 91	503.43 / 91	190.94 / 83	710.08 / 92	246.23 / 82	402.48 / 91	139.62 / 74	322.92 / 85

Table 1: The priors we used and the best-fit parameters for GM and CSM spectra. $a = 10^{-14}$; c = uniform priors in linear space were assumed. For all other parameters, log-uniform priors were assumed

The CSM spectra are rather similar to the GM spectra in that the silicon/sulfur line emission and/or iron-line emission are much less prominent than for typical spectra from Cas A (c.f. spectra in Hwang & Laming 2012). The abundance pattern for the GM spectra is also similar to those of the CSM spectra.

Evidence 2: Principal Component Analysis

It is difficult from spectral fitting alone to establish whether the GM spectra originate from metal-rich ejecta plasma, with a strong nonthermal component, or originate from CSM. To better characterize the spectral content, we resorted to PCA. We represent the spatial-plus-energy data cube as a 2D matrix, with the rows corresponding to all the spatial pixels (rebinned to 4 by 4 Chandra pixels) and the columns corresponding to discrete energy bands as stated in Table 2. The columns were centered (mean per band subtracted) and divided by the square root of the pixel variance for each band.

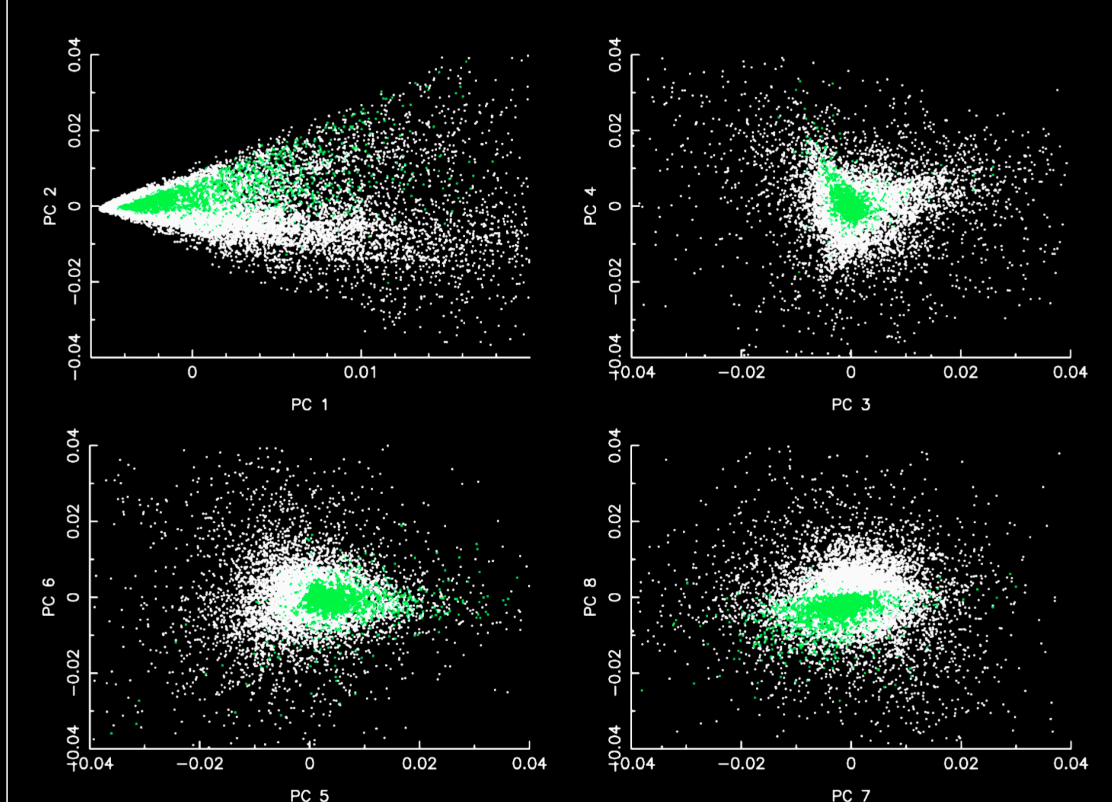


Fig 2: Scatterplot of PC scores for all pixels (white) and those corresponding to the GM (green), zoomed in where the majority of points are located.

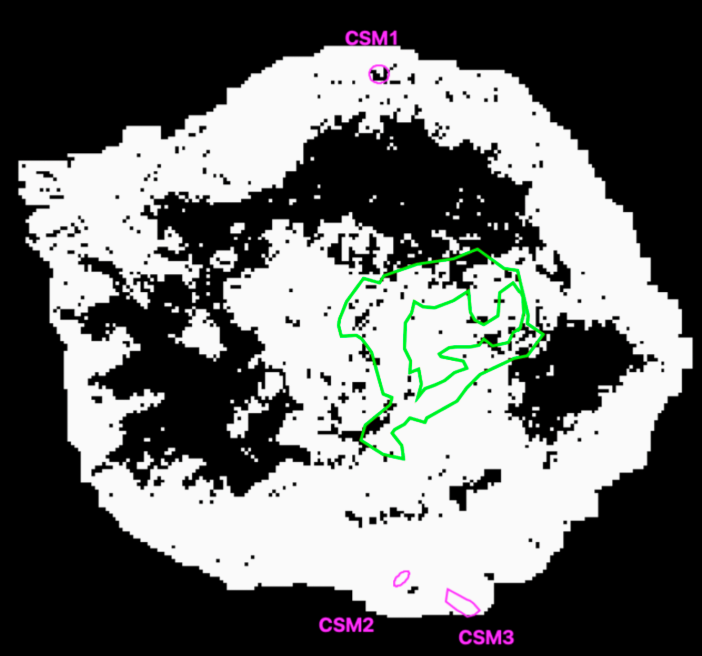


Fig 3: Mask created from the PC1 to PC8 scores using values corresponding to the green-colored regions in Fig 2.

The PCA output consists of the eigenvectors (principal components, PCs), singular values, and PC scores. The latter are images indicating for each pixel the amount by which it is represented by a PC. PCA regularizes data as a set of orthogonal components, whereas different physical components in the spectra may not necessarily be orthogonal and be spread over different PC scores. We take the first eight PCs (see Fig. 2). We use the scatter plots to create a mask of all regions similar to the GM by selecting Chandra pixels with PC score values in the high point density in the scatter plot for the GM region. We see that the mask selects out all regions associated with the main shell and, instead, most of the outer regions, where we expect the shocked CSM plasma to reside, are selected.

	E_min (keV)	E_max (keV)		E_min (keV)	E_max (keV)
1	0.50	0.62	15	2.63	2.78
2	0.62	0.72	16	2.78	3.00
3	0.72	0.87	17	3.00	3.28
4	0.87	1.03	18	3.28	3.60
5	1.03	1.12	19	3.60	3.75
6	1.12	1.23	20	3.75	4.04
7	1.23	1.42	21	4.04	4.50
8	1.42	1.56	22	4.50	5.00
9	1.56	1.69	23	5.00	5.40
10	1.69	1.85	24	5.40	5.75
11	1.85	1.98	25	5.75	6.25
12	1.98	2.13	26	6.25	6.62
13	2.13	2.28	27	6.62	6.85
14	2.28	2.63	28	6.85	7.35

Table 2: Input energy bands for PCA

Conclusions

Green Monster is dense circumstellar material ($n_e t \approx 1.5 \times 10^{11}$ cm^{-3}s) **on the near-side of Cas A** (radial velocity ≈ -2300 km/s) **that has been heated by the forward shock**

Read the full article!
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Questions? Collaborations?
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