XMM-Newton Observations of the Galactic Supernova Remnants G32.4+0.1 and G359.1-0.5

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Abstract: While nearly 300 supernova remnants (SNRs) are now known to exist in our Galaxy, only a tiny fraction of these sources have been studied in significant detail at multiple wavelengths. To remedy this situation and to improve our knowledge of general properties of SNRs and SNR-related phenomena, we are analyzing a sample of pointed archival X-ray observations made of poorly-studied Galactic SNRs with the *XMM-Newton* Observatory. We present here our spatially-resolved spectroscopic analysis of two of the sources in our sample – G32.4+0.1 and G359.1-0.5 – which exhibit unusual X-ray properties for Galactic SNRs. While the majority of Galactic SNRs produce X-ray emission via the thermal bremsstrahlung process, the X-ray emission from G32.4+0.1 appears to instead be synchrotron radiation from cosmic-ray electrons accelerated by the SNR. Furthermore, while the X-ray morphologies of Galactic SNRs are shell-like, the X-ray morphology of G359.1-0.5 is center-filled.

Background and Motivation:

- Few Galactic supernova remnants (SNRs) have been studied extensively at multiple wavelengths (such as X-ray and radio) such as X-Ray, optical, and radio
- Detailed multi-wavelength studies of more Galactic SNRs will improve our understanding of SNRs and SNR-related phenomena in general and individual Galactic SNRs in particular, embodied in the analysis of archival XMM-Newton Observations of Galactic SNRs to yield new insights into these sources (Onic, Porter, Pannuti, et al. 2019, Astronomy & Astrophysics, in press)
- G32.4+0.1 and G359.1-0.5 are two poorly-studied Galactic SNRs that have been the subjects of pointed observations made with the *XMM-Newton* X-ray Observatory
- We are conducting a spatially-resolved X-ray spectroscopic study of these two sources to determine the nature of their observed X-ray emission (synchrotron or thermal bremsstrahlung) detected from these sources

Spectra of SNRs at X-ray energies:

- Bremsstrahlung radiation (Figure 1.1): electrons emit photons as they pass nuclei and they are accelerated.
- Synchrotron radiation (Figure 1.2): relativistic electrons emit photons as they gyrate in magnetic fields.
- Detailed analysis of extracted X-ray spectra from SNRs can determine which process is producing the observed emission (based on slope of spectrum)

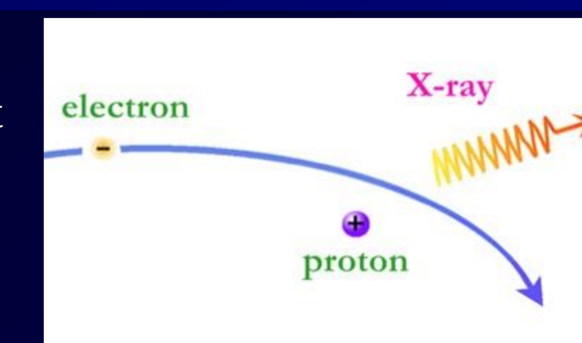

Figure 1.1

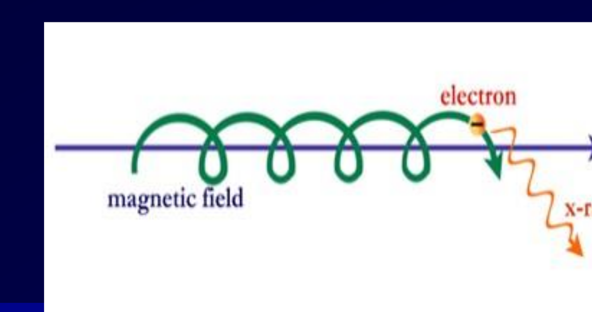

Figure 1.2

G32.4+0.1

G32.4-0.1 exhibits a shell-like radio morphology at radio wavelengths with an angular diameter of approximately 6 arcminutes and an integrated flux density of 0.25 Jy at 1 GHz (Yamaguchi et al. 2004). It was initially discovered by the ASCA (Advanced Satellite for Cosmology and Astrophysics) Galactic Plane Survey as a diffuse source of hard (predominately high energy) X-ray emission (Yamaguchi et al. 2004). Detailed X-ray spectroscopic analysis reveals that the emission is synchrotron in origin and is produced by cosmic-ray electrons that have been accelerated to relativistic velocities by the expanding shock front of the SNR. This result contrasts with the typical X-ray emission from SNRs which is chiefly thermal in origin and is produced by a hot X-ray-emitting plasma. G32.4-0.1 produces synchrotron radiation from the radio portion of the electromagnetic spectrum all the way through the X-ray and is one of the few known SNRs which emits (apparently) exclusively synchrotron radiation in the X-ray.

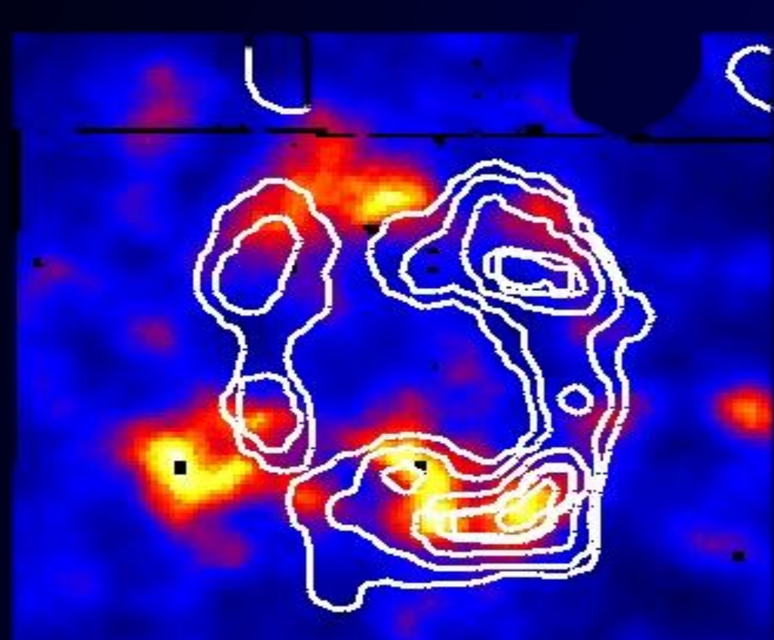

Figure 2: Exposure-corrected and adaptively-smoothed *XMM-Newton* MOS1+MOS2+PN X-ray image of G32.4+0.1 over the energy range 2.0 keV to 7.0 keV. Radio emission as detected by the Very Large Array at a frequency of 1.4 GHz is shown as overlaid contours. The southeastern rim appears to be prominent in both the radio and the X-ray while other regions of the SNR lack strong agreement in these two wavelength domains.

Parameter	Southern Rim	Whole SNR
N_H (10^{22}cm^{-2})	$12.92\pm^{9.08}_{5.90}$	$3.30\pm^{1.17}_{0.93}$
Γ ($E^{-\Gamma}$)	$3.75\pm^{2.19}_{1.52}$	$1.86\pm^{0.41}_{0.37}$
Normalization (Photons keV^{-1} cm^{-2} s^{-1} at 1 keV)	$3.30\text{x}10^{-3}$	$6.08\text{x}10^{-4}$
χ^2/Degrees of Freedom (DOF)	72.04/66	266.38/241
$\Delta\chi^2$	1.09	1.11

Table 1: Summary of parameters of fit to spectra extracted for the southern rim of G32.4+0.1 (as well as the whole SNR) using the TBABSx Power Law model. The fitted value of the photon index for the whole SNR is consistent with synchrotron radiation while the fitted value of the photon index for the southern rim implies a mixture of synchrotron radiation and bremsstrahlung.

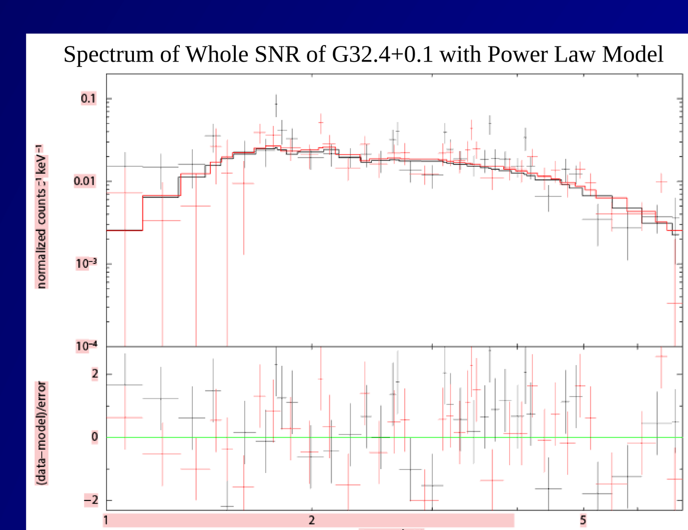

Figure 3: *Top Panel* – The extracted MOS1+MOS2 spectra (depicted in black and red respectively) of the entire extent of G32.4+0.1 as fit with the (TBABS*APEC)+(TBABS*VRNEI) model. The former component fits the diffuse Galactic ridge emission while the latter component fits the emission from G359 itself. See Tables 1 and 2 for the fit parameters.

G359.1-0.5

G359.1-0.5 exhibits a shell-like morphology at radio wavelengths with an angular diameter of 24 arcminutes and an integrated flux density of 14 Jy at 1 GHz (LaRosa et al. 2000, Yusef-Zadeh et al. 2004). The X-ray morphology of this SNR is not shell-like but instead is center-filled: spatially-resolved spectroscopic analysis of this X-ray emission indicates that it is thermal in origin (Ohnhishi et al. 2011). The contrasting X-ray and radio morphologies of this SNR coupled with the thermal origin of its X-ray emission motivates its classification as a mixed-morphology SNR, an emerging class of sources that may indicate a new evolutionary scenario for SNRs (Rho & Petre 1998, Pannuti et al. 2014). Like other mixed-morphology SNRs, G359.1-0.5 appears to be interacting with adjacent molecular clouds as evidenced by the detection of a hydroxyl maser and a shocked molecular cloud along the periphery of the SNR. This interaction is believed to drive the formation of the center-filled morphology seen in mixed-morphology SNRs but the details of this mechanism remain unclear.

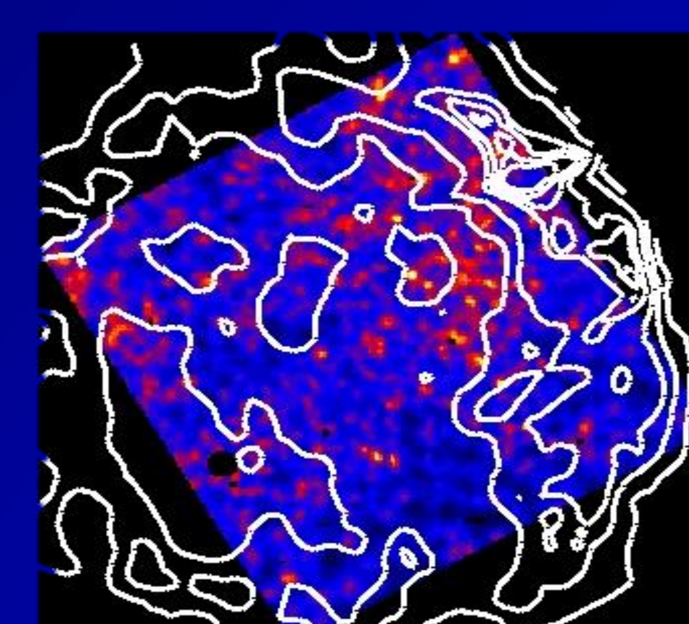

Figure 4: Exposure-corrected and adaptively-smoothed *XMM-Newton* MOS1+MOS2+PN X-Ray image of G359.1-0.5. Radio emission as detected by the Very Large Array is shown as overlaid contours. Radio wavelengths appear to show a shell-like morphology, while X-Ray emission contrasts by being center-filled. This shape suggests a new mixed-morphology classification.

Parameter	G359.1-0.5
N_H	2.43 ± 0.4 x cm^{-2}
kT (keV) (electron)	0.27 ± 0.10
kT (keV) (plasma)	1.09 ± 0.20
Si Abundance (solar)	4.37 ± 0.5
S Abundance (solar)	5.57 ± 0.6
Ionization Timescale (s)	$1\text{x}10^{11}cm^{-3}$
Normalization (1keV)	2.59x $10^{-2}cm^{-5}$

Table 2: Summary of parameters of fit to spectra extracted for G359.1-0.5 using the TBABSx Power Law model. The ionization timescale suggests that the SNR is much older than behavior shows, illustrated through the Si and S abundance being that of a much younger remnant. The reason behind such behavior and mixed-morphology remain unknown.

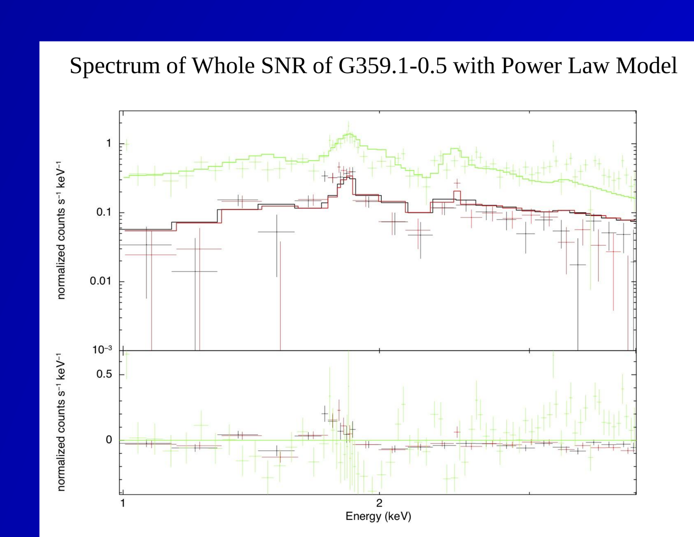

Figure 5: *Top Panel-* The extracted MOS1+MOS2 and PN spectra (depicted in black, red, and green respectively) of the entire extent of G359.1-0.5 as fit with the TBABSxPower Law model using the parameters listed in Table 1.
Bottom Panel- Residuals to the fit.

Parameter	Galactic Ridge Component
N_H	6x 10^{22}cm^{-2}
kT (keV)	15.0
Normalization (Photons keV^{-1} cm^{-2} s^{-1} at 1 keV)	$8.77\text{x}10^{-3}$ cm^{-5}

Table 3: Summary of parameters of fit of diffuse X-Ray emission in Galactic Ridge using the TBABS*VRNEI model. The TBABS element quantifies absorption by the interstellar medium along the line of sight while the VRNEI element describes the temperature , elemental abundances, and ionization timescale (which are unclear indicates if the plasma is in collisional ionization equilibrium or not) of a thermal X-ray plasma. The enhanced abundances of silicon and sulfur relative to solar indicates the presence of ejecta-dominated plasma: such elevated abundances are unexpected for an evolved SNR like G359.1-0.5. The reason for the presence of such a plasma at an advanced evolutionary stage and for the mixed morphologies of this SNR

References

LaRosa et al. 2000, AJ, 119, 207, Lazendic et al. 2002, MNRAS, 331, 537, Ohnhishi et al. 2011, PASJ, 63, 527, Onic, Porter, Pannuti, et al. 2019, Astronomy & Astrophysics, in press, Pannuti et al. 2014, AJ, 147, 55, Rho & Petre 1998, ApJ, 503, L167, Yamaguchi, H. 2004, PASJ, 56, 1059, Yusef-Zadeh et al. 2004, ApJS, 155, 421

Conclusion:

In summation, while the X-ray morphologies of SNRs are typically shell-like, G359.1-0.5 is unique in that its X-ray morphology is center-filled. The mixed-morphology class that G359.1-0.5 resides in may result in new evolutionary pathways for SNRs as they progress. In addition, we conclude that G32.4+0.1 has X-ray emission resulting from synchrotron radiation. This radiation results from cosmic-ray electrons gyrating in magnetic fields which are amplified by the SNR in study. These properties exhibited by each SNR are relevant in understanding how to classify and further research other SNRs that may showcase similar properties.