Fe K and ejecta emission in SNR G15.9+0.2 with XMM-Newton

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Abstract: We present a study of the Galactic supernova remnant SNR G15.9+0.2 with archival XMM-Newton observations. Using EPIC's collective power, we report for the first time the detection of Fe K line emission from SNR G15.9+0.2. We measure the line properties (e.g. centroid energy and width) and find evidence for spatial variations. We discuss how SNR G15.9+0.2 fits within the current sample of SNRs with detected Fe K emission and found that it is the core-collapse SNR with the lowest Fe K centroid energy. We also present some caveats to the use of Fe K line centroid energies as typing tools for SNRs.

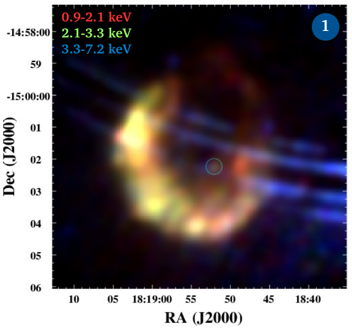
We analyse the emission-line rich X-ray spectra extracted from various regions. The abundances of Mg, Si, S, Ar, and Ca are super-solar and their ratios strongly suggests that the progenitor of SNR G15.9+0.2 was a massive star, strengthening the physical association to a candidate Central Compact Object detected with Chandra.

Using the absorption column density and ambient medium density constrained by the X-ray spectral analysis, we revise the measurements of the age and distance to the SNR.

I) Introduction

SNR G15.9+0.2 was discovered in radio by Clark et al. (1973,1975). The SNR is relatively bright in X-rays, as found in *Chandra* data by Reynolds et al. (2006, hereafter R06). Although 300 SNRs are now known in the Milky Way, SNR G15.9+0.2 is an interesting target for an in-depth analysis with XMM-Newton for several reasons:

- **It is likely young** ($\sim10^3$ yr), as suggested by R06. Adding G15.9 to the sample of SNRs less than 2000 yr old would reduce the discrepancy between the observed and expected number of young SNRs.
- It hosts a **candidate central compact object (CCO)**. There are only 7 confirmed CCOs and 7 candidates (including G15.9).
- Its young age and plasma conditions should produce **detectable Fe K emission**. Yamaguchi et al. (2014) found that the Fe K centroid energy is an efficient tool to distinguish type Ia SNRs (Fe K at 6.4 keV) and core-collapse SNRs (Fe K at 6.7 keV). If Fe K emission can be detected, we will obtain independent clues to the origin of the remnant.



II) Observations and X-ray Image

SNR G15.9+0.2 was serendipitously observed twice at off-axis angles of 8' to 12'. Filtered and vignetted exposure times are 33 and 47 ks. We created images and exposure maps in three energy bands tailored to its spectrum (R06). The detector-background-subtracted images from the two observations (pn + MOS) were merged, adaptively smoothed, and divided by the corresponding vignetted exposure map.

The composite X-ray image of SNR 15.9+0.2 is shown in **Fig. 1.** The annular stripes at high energy (in blue) are straylight emission, unrelated to the SNR. The position of the CCO candidate, which is detected with less than 200 counts, is marked (cyan circle).

The source exhibits a well-defined shell morphology, with the eastern and south-western edges particularly bright. In contrast, the north-western quadrant of the shell is much fainter and softer. **This quadrant that was not detected with *Chandra* complete the X-ray shell.** The shell is a slightly elongated ellipse, with major and minor axes of 6.2' and 5.2'. The CCO candidate is offset 44" from the visual centre.

III) Spectral Analysis

We extracted X-ray spectra from various regions of the remnant, as shown in **Fig. 2 (centre)**. We used the method described in Maggi et al. (2016): We simultaneously fit the source and background spectra, with the instrumental, astrophysical, and straylight contributions to the background explicitly modeled. The source emission (Fig. 2) is thermal with many strong lines from Mg, Si, S, Ar, and Ca. It is severely cut off at soft energy, indicating a high absorption. The spectra are well fit with an under-ionised plane-parallel shock model. Abundances must be super-solar to reproduce the strong lines, betraying an ejecta origin.

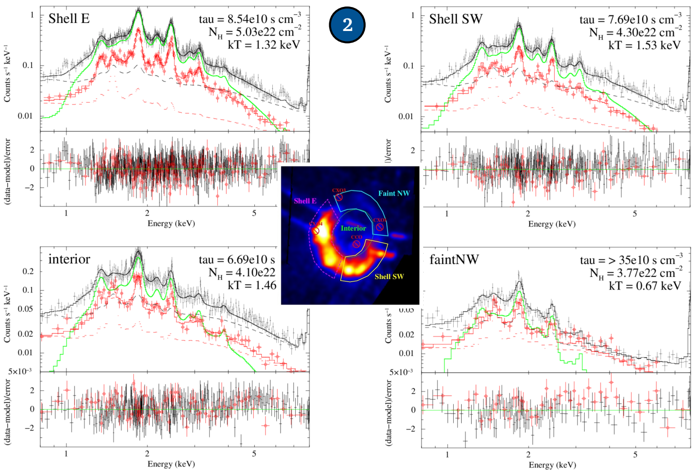
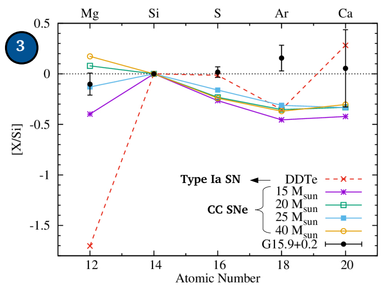


Figure 2: X-ray spectra in several regions (defined in the central inset). For clarity, only pn and one of the MOS2 spectra are shown, in black and red. All background components are shown by the dashed lines. Parameters of the source model (green line) are listed. The temperatures and ionisation ages (tau = $n_e t$) are about the same in the shell regions and in the interior. The Faint NW emission is the most different: Abundances are only slightly above solar, and N_H is the lowest. The absorption is the highest in the east. A likely explanation for this is given in Part IV (see Fig. 6).

IV) Results and Discussion

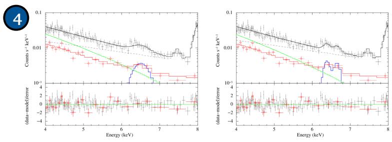


Type of Progenitor

The abundance pattern in the ejecta contains clues to the progenitor type of SNR G15.9+0.2. In **Fig. 3**, we plot abundances relative to Si (by number), in the form [X/Si] = log[(X/Si)/(X/Si)$_{sun}$], using the results of the spectral analysis on the spatially integrated spectrum (black dots).

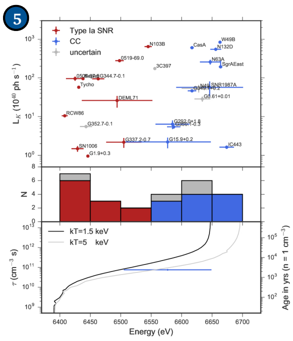
We compare with predicted nucleosynthesis yields for core-collapse (CC, Nomoto et al. 2006) and type Ia SNe (Badenes et al. 2003). They are best set apart by the Mg/Si ratio: All type Ia models produce very little Mg. In massive stars, Mg yields is higher and varies strongly with the progenitor mass. The [Mg/Si] ratio in G15.9 is 40 times that predicted for a type Ia SN, while consistent with several CC models. **This is a strong indication that the progenitor of G15.9 was a massive star, strengthening the physical association of the CCO candidate to the SNR.**

Evolution of Fe K emission in SNRs



Fe K emission is significantly detected in G15.9. In the "shell E" spectrum, the line complex is best fit with a Gaussian with free width at 6.52 keV **(Fig. 4, left)**, or two narrow Gaussians at 6.4 and 6.7 keV **(Fig. 4, right)**.

This indicates contributions from both lowly- and highly-ionised iron, pointing to a range of $n_e t$ due to variations in the ambient density encountered by the shock. The total Fe K emission from G15.9 is fit by a Gaussian at 6.58 keV with width of 155 eV.

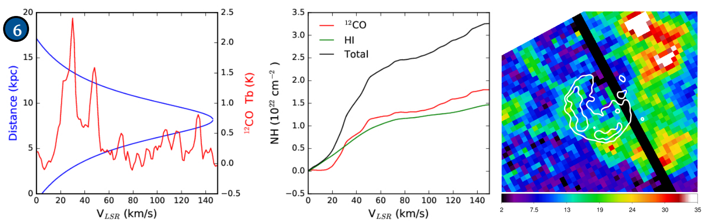


The luminosity-centroid energy diagram of the Fe K line in SNRs is shown in **Fig. 5 (top panel)**, using results of Yamaguchi et al. (2014), Maggi et al. (2016). We added SNR G15.9+0.2. It is the CC SNR with the lowest centroid energy. The distribution of SNRs of either type as function of centroid energy **(Fig. 5, middle panel)** has a valley at 6.55 keV due to the rapid transition between a roughly 6.4 keV centroid (no iron above the Fe XVII and a 6.6-6.7 keV centroid (most iron above Fe XX).

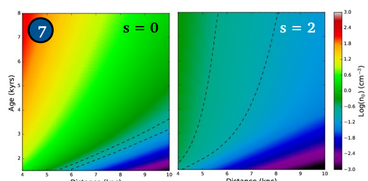
We simulated the expected centroid of a pure-iron ionising plasma **(Fig. 5, bottom panel)** to illustrate this rapid transition of Fe K between a $n_e t$ of a few 10^{10} and a few 10^{11} s cm^{-3}, corresponding to an age of 1000-5000 yr for an ambient medium density of 1 cm^{-3}.

The oldest type Ia SNRs in that sample are about 5000 yr old but associated to density of 0.3-0.8 cm^{-3}, so that a low Fe ionisation is expected even at this age. The possibility remains open for a type Ia SNR in a denser medium (> 2 cm^{-3}) to reach a high ionisation of iron within a few thousand years. Symmetrically, it is not excluded that some CC SNRs be found in the low ionisation end. **We conclude that the Fe K centroid-luminosity diagram provides valuable information about an SNR, but care should be taken when using it as a typing tool without any knowledge of the surrounding medium or indication of age.**

Age and Distance of SNR G15.9+0.2



The ^{12}CO spectrum at the position of the source is shown in **Fig. 6 (left, red line)**, with corresponding kinematic distance in **blue.** The total N_H (HI+^{12}CO) towards the source is shown in the **middle panel.** The large N_H found in X-rays indicates a large distance. As the bulk of the material is at V_{LSR} < 60 km s^{-1}, **a distance of 5 kpc is a *conservative* lower limit.** On **Fig. 6 (right panel)**, we show the higher resolution ^{13}CO intensity map (18<V_{LSR}<32 km s^{-1}), with X-ray contours overlaid. Small clouds are seen at the position of the "shell E" and "shell SW" regions, explaining the higher N_H found there (see Fig. 2).



For a given ejecta mass and explosion energy, the age and physical size of the remnant are connected by the ambient density n_0, which is n_0 = (0.36 - 0.70) (D/5kpc)$^{-1/2}$ cm^{-3} in the region least affected by ejecta (faint NW).

We produced age-distance-density diagrams for an SNR expanding into a uniform ambient density **(s=0, Fig. 7, left)** or in a progenitor's wind **(s=2, Fig. 7, right)** using the equations of Truelove and McKee (1999) & Laming and Hwang (2012). We overlay in both cases the constraints on density. **For realistic distances D>>5 kpc, the likely age of SNR G15.9+0.2 is in excess of 2000 yr.**

V) Summary

- SNR G15.9+0.2 exhibits a shell morphology with the brightest regions in the east and south-west, and the faintest and softest to the north-west.
- Analysis of the ejecta abundance pattern establishes SNR G15.9+0.2 as a core-collapse SNR, strengthening the physical association with the candidate CCO detected in its interior.
- We report for the first detection of Fe K emission from SNR G15.9+0.2, with signal at both the low and high-ionisation end of the line. The overall energy centroid is the lowest of any core-collapse SNRs.
- Comparing the X-ray derived absorption with HI and CO data, we set a conservative lower limit of 5 kpc for the distance towards the source. For such large distances, the SNR is likely older than 2000 years.

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