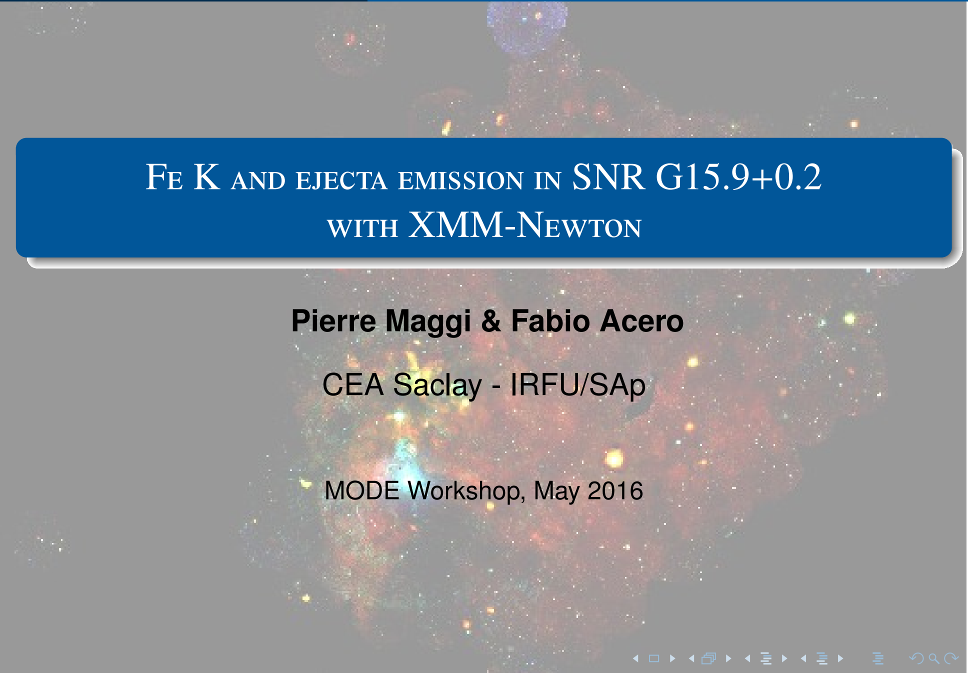

FE K AND EJECTA EMISSION IN SNR G15.9+0.2 WITH XMM-NEWTON

Pierre Maggi & Fabio Acero

CEA Saclay - IRFU/SAp

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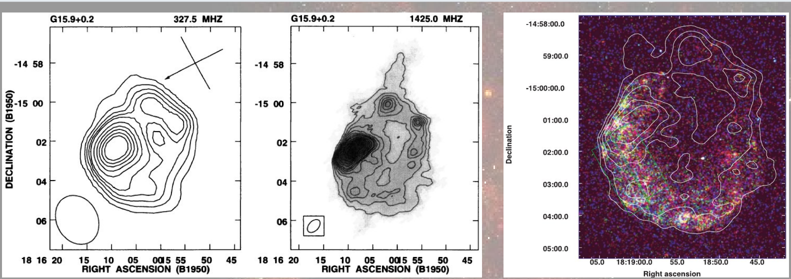
SNR G15.9+0.2, AN ORDINARY GALACTIC SNR

- Discovered in Molonglo-Parkes observations (Clark et al. 1973, 1975).
- Elongated shell-like structure, bright enhancement on the eastern border (Dubner et al. 1996).
- Spectral index $\alpha = -0.6$, steeper on the east.
- Relatively bright in X-rays (*Chandra* observations of Reynolds et al. 2006).
- IR-emitter (24 μm), morphology similar to radio and X-rays (Pinheiro Gonçalves et al. 2011).



Left/middle: VLA images of SNR G15.9+0.2 (Dubner et al. 1996).
Right: *Chandra* image with radio contours (Reynolds et al. 2006).

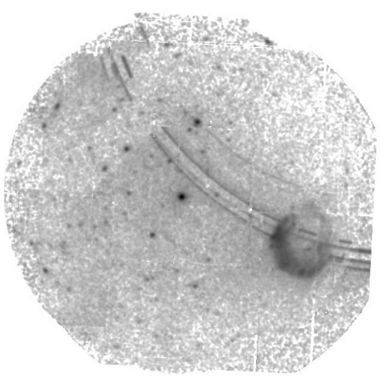
SNR G15.9+0.2, an interesting Galactic SNR

Three key features :

1. It is likely young ($\sim 10^3$ yr), based on *Chandra* analysis
   ↪ only 15/300 Galactic SNRs are $\lesssim$ 2000 yr.
2. It hosts a candidate Central Compact Object (CCO, isolated neutron star)
   ↪ only 7 confirmed CCO and 7 candidates (Halpern & Gotthelf 2010).
3. It potentially produces Fe K emission (at 6.4–6.7 keV, depending on $\tau = n_e t$)
   ↪ Yamaguchi et al. (2014) used the Fe K centroid energy to distinguish type Ia SNRs (Fe K at $\sim$ 6.4 keV) and core-collapse SNRs (Fe K at $\sim$ 6.7 keV).

⟹ XMM-Newton is well suited to elaborate and improve previous studies :

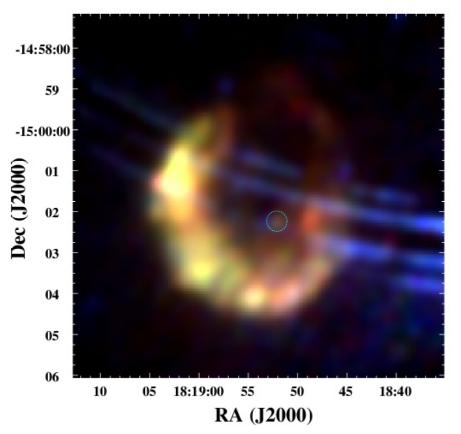
- 5× better effective area at 6.4 keV, ideal for Fe K study.
- Detect and characterise X-ray emission in the north-western quadrant.
- Measure abundances and plasma conditions in different regions.
- Reassess the age and distance of SNR G15.9+0.2 (with other tracers).



Field of view of the Full Frame observation.

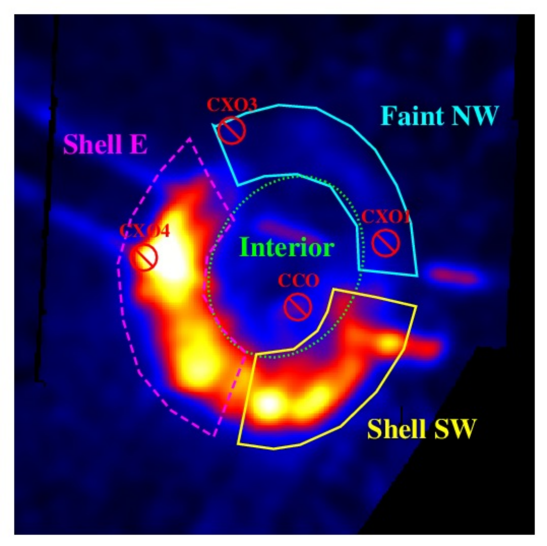
- The observations were targeted on PSR J1819−1458, a “Rotating RAdio Transient” (RRAT), ~ 10’ away from the SNR.
- Even with vignetting, the available data have very good statistics.
- Annular stripes are straylight, single-reflections from bright off-axis source.

ObsID	Date	Filtered exposure time (ks)	EPIC mode
0406450201	2006 Apr 6	33	Small Window
0505240101	2008 Mar 31	47	Full Frame

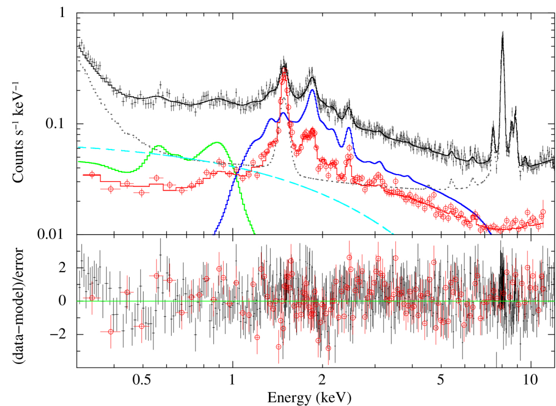


Adaptively smoothed, exposure corrected RGB composite, using energy bands : (0.9 - 2.1 keV)/(2.1 - 3.3 keV)/(3.3 - 7.2 keV)

- Mostly similar to *Chandra* image.
- Faint emission in the north-west, as is seen in radio and infrared.
- The CCO is detected (circle).



Definition of regions for spectral analysis.

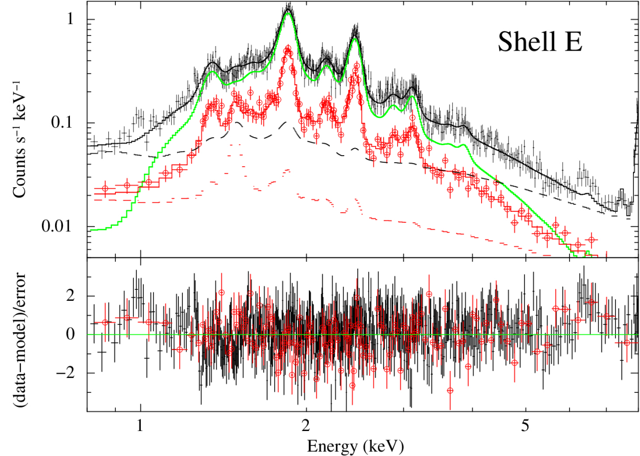


Background spectrum of SNR G15.9+0.2. pn and MOS2 data in black and red.

$$S = S_{\mathrm{instrumental}} + S_{\mathrm{AXB}} + S_{\mathrm{protons}}$$

$$S_{\mathrm{AXB}} = S^{1}_{\mathrm{apec}} + S^{2}_{\mathrm{apec}} + \mathtt{phabs}(N^{1}_{H})\left(S^{3}_{\mathrm{apec}} + \mathtt{phabs}(N^{2}_{H}) N_{\mathrm{CXB}} E^{-\Gamma}\right)$$

NB: No detection of Fe K emission from Galactic Ridge X-ray emission.



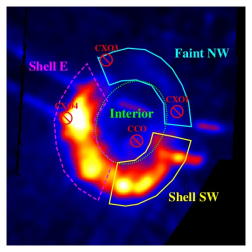
X-ray spectra in the “Shell E” regions. pn and MOS2 data in black and red.

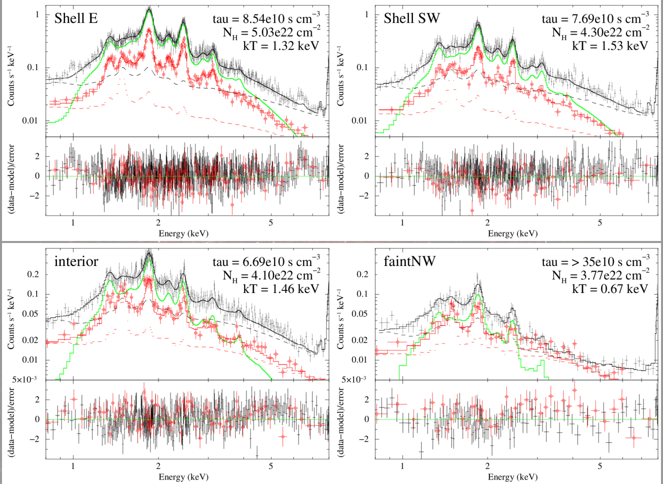
All background components (including straylight) are shown by the dashed lines.

Main features of source: Strong lines (Mg, Si, S, Ar, Ca); high absorption.

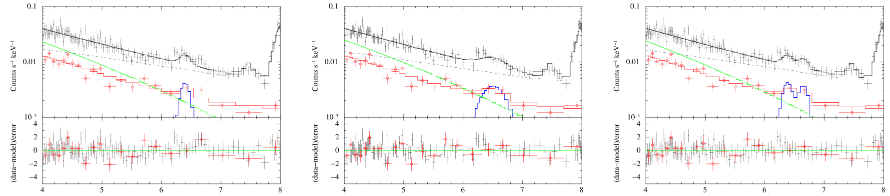
Best-fit SNR model (green): Plane-parallel shock, underionised, free abundances.

SPECTRAL ANALYSIS : BEST-FIT MODELS

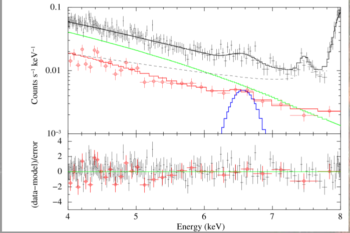




X-ray spectra with key parameters in all regions (tau $= \int_0^t n_e dt$).



The spectrum around 6.4 keV in the Shell E region. Background is shown by the dashed line, the SNR continuum and Fe K line in green and blue, respectively. *Left :* Zero-width Gaussian; *middle :* Free-width Gaussian; *Right :* Two Gaussians.

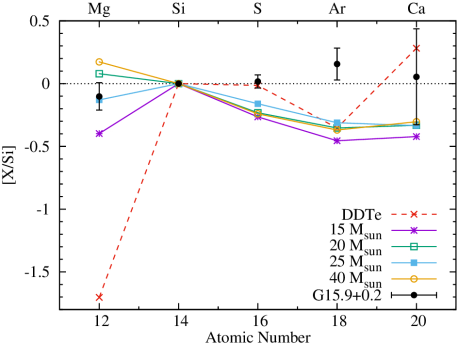


↦ The same in the “bright” region (Shell E + SW).

Fit with free-width Gaussian, for comparison with results from Yamaguchi et al. (2014): $E = 6577(^{+73}_{-70})$ eV, width $\sigma = 155$ eV.

Equally good fit with a two-Gaussians model: $E_1 = 6411(\pm 46)$ eV and $E_2 = 6670(^{+34}_{-41})$ eV.

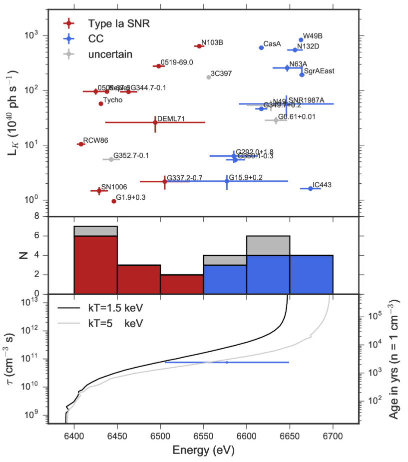
Absolute abundances are 1.5 to 3 times solar, revealing ejecta contribution.
↪ Abundance **ratios** can help to identify the type of progenitor.



Abundance ratios [X/Si] ≡ log $[(X/Si)/(X/Si)_\odot]$, measured in SNR G15.9+0.2 (black dots).
Solid lines: Predicted yields of CC SNe of various progenitor masses (Nomoto et al. 2006).
Dashed line: Yields for a delayed-detonation model of type Ia SN (Badenes et al. 2003).

- [Mg/Si] provides a strong argument for a core-collapse origin.
- Strengthens the case for a Central Compact Object.

EVOLUTION OF FE K LINES IN SNRS



Top : Centroid enery and luminosity of Fe K lines detected in SNRs. Results from Yamaguchi et al. (2014, 23 objects), Maggi et al. (2016), this work.

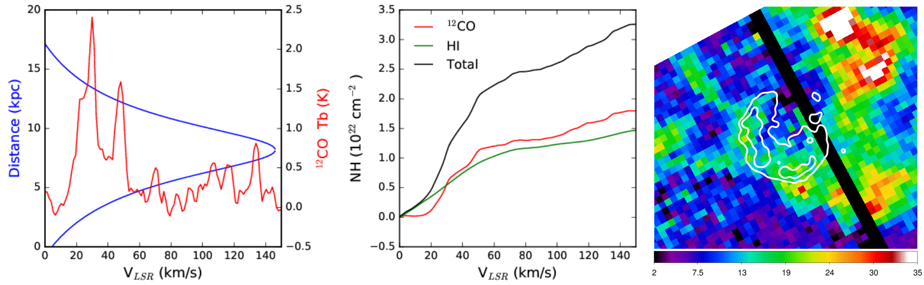
Middle: Distribution of SNRs of either types vs. Fe K energy.

Bottom: Expected centroid energy vs. τ, with best-fit τ and range of centroid energy for G15.9+0.2 indicated. Note the rapid transition (at a few $10^{10} - 10^{11}$ s cm^{-3}). G15.9+0.2 is the CC SNR with the lowest Fe K energy, some regions still at 6.4 keV.

- Still possible for a type Ia SNR in $\rho_0 \gtrsim 2$ cm^{-3} to reach 6.7 keV in a few 10^3 yr.
- Age bias: 6 type Ia SNR younger than 1000 yr, 3 CC SNR below 2000 yr.

↦ Care should be taken when using the Fe K line as a typing tool without any knowledge of the surrounding medium or indication of age.

AGE AND **distance** OF SNR G15.9+0.2



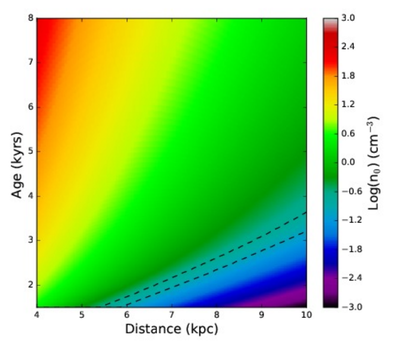
Left : ^{12}CO spectrum at the position of the SNR (red). The corresponding kinematic distances are shown in blue. *Middle :* Integrated N_H (HI + ^{12}CO) as function of velocity. *Right :* X-ray contours on ^{13}CO intensity map ($V_{LSR} = 18 - 32$ km s^{-1}).

- The observed total N_H falls short of the X-ray-measured $N_H^X \sim 4 \times 10^{22}$ cm^{-2} : Uncertain X_{CO}, contribution from ^{13}CO could resolve this discrepancy.
- The high resolution ^{13}CO map reveals small clouds, explaining the absorption variations across the SNR.

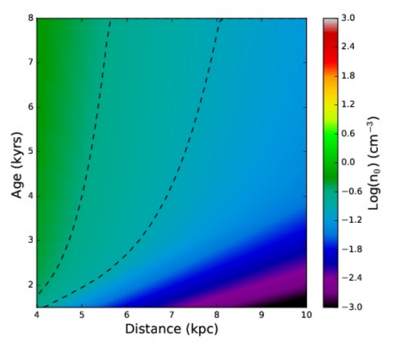
↦ Bulk of the material is at $V_{LSR} \lesssim 50$ km s^{-1}, i.e. 5 kpc is a conservative lower limit for the distance to SNR G15.9+0.2, likely more.

↦ For a given progenitor mass and explosion energy, the age and physical size of the remnant are connected, depending on the ambient density n_0.

Density n_0 constrained via the X-ray Emission Measure (EM $\equiv \int n_e n_H dV$) in the Faint NW region : $n_0 = (0.36 - 0.70)\left(\frac{D}{5\ \mathrm{kpc}}\right)^{-1/2}\ \mathrm{cm}^{-3}$.



Propagation in uniform ambient medium.



Propagation in a wind ($n(R) \propto R^{-2}$).

A bright X-ray shell in in the east and south-west

- Ejecta contribution
- Enhanced absorption, possibly from foreground clouds

Faint X-ray emission in the north-west

- Little ejecta contribution, less absorption
- Used to constrain ISM density

↦ Abundance ratios strongly suggest a core-collapse origin

Fe K emission

- Varying conditions, even low-ionised iron
- A tool to use with caution

- A kinematic distance much in excess of 5 kpc
- For various ambient medium, an age likely more than 2000 yr