Evolved Fe-rich supernova remnants in the Large Magellanic Cloud with Athena

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Recently, a new class of evolved supernova remnants (SNRs) with centrally peaked Fe-rich emission has been identified in the Magellanic Clouds. They contain X-ray bright Fe-rich cores, consistent with reverse shock-heated Type Ia ejecta (Borkowski et al. 2006). The Fe gas is cool (kT \approx 1 keV) and is dominated by Fe L-shell transitions, with a prominent forest of lines in the 0.7–1.1 keV range. Observations with the current generation of X-ray facilities show that the interior Fe-rich plasmas exhibit long ionisation ages consistent with collisional ionisation equilibrium (CIE), requiring higher central densities than expected from standard Type Ia models. The prompt' single degenerate Type Ia systems (Mannucci et al. 2006), produced by intermediate mass stars just below the core-collapse explosion limit (~3.5–8 M☉, Aubourg et al. 2008), are capable of enhancing the circumstellar medium density via ejection of the stellar envelope prior to the supernova event. Softer X-ray emission from a shell of swept-up dust and shock-heated interstellar medium (ISM) may be present in some. The absence of a soft shell might be expected if the SNR is close to the transition into the radiative phase and the shell has become either too cool to emit X-rays or too faint to be detectable. Additionally, O ejecta have been observed in some, which is expected given that it is the second most abundant nucleosynthesis product of Type Ia explosions (e.g., Iwamoto et al., 1999). As examples, we present the two most recently identified members of the class, MCSNR J0506–7025 and MCSNR J0527–7104 observed by XMM-Newton from Kavanagh et al. (2015).

**MCSNR J0506–7025**

This SNR is characterised by a bright core in the 0.7–1.1 keV range, surrounded by a soft shell evident in the 0.3–0.7 keV band (Fig. 1-top left). The enhanced X-ray emission in this core is due to Fe rich gas in CIE with kT \approx 0.8 keV, the result of reverse shock-heating of the Fe ejecta. The soft shell is consistent with swept-up and shock-heated ISM with kT \approx 0.2 keV and \tau \approx 10^{11–12} s cm\(^{-2}\). Typical of an evolved SNR, the Sedov phase. The spectrum of MCSNR J0506–7025, along with the best fit model, is shown in Fig. 2-top left. This Fe core/shell morphology has been observed in several other members of the class, including DEM L238 and DEM L249 (Borkowski et al. 2006) and MCSNR J0506–6902 (Bozzetto et al. 2014).

**MCSNR J0527–7104**

This SNR exhibits an extremely unusual morphology. The characteristic Fe-rich gas in CIE is observed with kT \approx 0.7 keV and dominated by Fe L-shell lines. However, the emission extends from the southeastern optical shell, right through the southeastern-northwest axis of symmetry, appearing to escape or blow-out the northwestern shell (Fig. 2-bottom row). Multi-wavelength evidence for a blow-out was found by Kavanagh et al. (2015). The absence of soft X-ray emission within the optical shell suggests that the remnant is close to the transition into the radiative phase with either faint or absent X-ray emission. Other LMC remnants to exhibit similar properties include MCSNR J0506–6830 and MCSNR J0511–6659 (Maggi et al. 2014), though these have somewhat less distorted Fe cores.

**Athena X-IFU**

The diagnostic potential of Fe L-shell transitions has been discussed often in the literature (e.g., Kavanagh et al. 2014). K-shell lines dominate the intrinsic luminosity of several ionisation stages of Fe across a wide temperature range. The sheer variety of possible L-shell transitions gives rise to a forest of L-shell lines, considerably more rich than the often used Fe K-shell transitions. However, the limited spectral resolution of CCD detectors cannot resolve the individual lines of the Fe L-shell forest, instead giving rise to the L-shell 'bump' (see Fig. 2-top row) and often overlapping with emission lines of other elements such as Ne and Mg if present.

The grating spectrometers onboard Chandra and XMM-Newton do resolve the L-shell lines and have been used to obtain high resolution spectra of young and bright SNRs in the LMC (e.g., Kosenko et al., 2008, 2010). However, these applications are limited to less spatially extended sources of sufficient brightness.

The combination of the proposed effective area of Athena (Barcons et al., 2015) and the cryogenic X-ray spectrometer X-IFU (Ravera et al., 2014), with a resolution of 2.5 eV below 7 keV, will reveal many more cosmic sources at high spectral resolution than has been previously possible, including the evolved Fe-rich SNRs of the LMC. The FOV of the X-IFU (diameter = 5') can comfortably accommodate the extent of the Sedov phase of the Athena mirror providing a spectrally-resolved X-IFU response files for a 1.37 m² mirror using XSPEC version 12.8.2p and atomic data from ATOMDB 3.0.1 with the latest equilibrium and non-equilibrium data, shown in Fig. 2-bottom row. These simulations, albeit with current atomic databases, demonstrate the potential of Athena X-IFU for revealing the detailed plasma properties as well as providing a test of atomic databases.

**Simulations**

The correct interpretation of the astrophysical plasmas at issue relies heavily on the accuracy of the atomic database such as the AtomDB. Given the relatively pure and uncontaminated Fe L-shell emission in the evolved Fe-rich SNRs of the LMC, we suggest that these objects could provide an ideal test of the Fe L-shell transition databases. To illustrate this, we simulated 30 ks Athena X-IFU observations of MCSNR J0506–7025 and MCSNR J0527–7104 using the latest X-IFU response files for a 1.37 m² mirror using XSPEC version 12.8.2p and atomic data from ATOMDB 3.0.1 with the latest equilibrium and non-equilibrium data, shown in Fig. 2-bottom row. These simulations, albeit with current atomic databases, demonstrate the potential of Athena X-IFU for revealing the detailed plasma properties as well as providing a test of atomic databases.

**References**

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