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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 < 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 $M_\odot$, 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 and shock-heated interstellar medium (ISM), typical of an evolved SNR, is 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 to 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 0.7–1.1 keV emission in the core is due to an Fe rich gas in CIE with kT ~ 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 ~ 0.2 keV and $\tau \sim 10^{11\text{-}12}$ s cm^{-3}, typical of an evolved SNR in 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/soft shell morphology has been observed in several other members of the class, including DEM L238 and DEM L249 (Borkowski et al. 2006) and MCSNR J0508–6902 (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 ~ 0.7 keV and dominated by Fe L-shell lines. However, the emission extends from the southeastern optical shell, right through the southeast-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 J0508–6830 and MCSNR J0511–6759 (Maggi et al. 2014), though these have somewhat less distorted Fe cores.

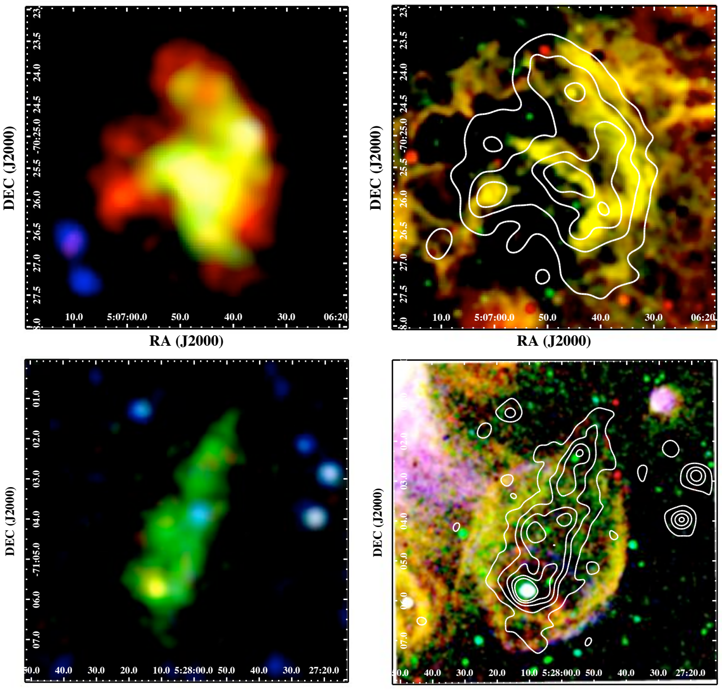

Fig. 1. Top left: *XMM-Newton* EPIC image of MCSNR J0506−7025 in false colour with RGB corresponding to 0.3–0.7 keV, 0.7–1.1 keV, and 1.1–4.2 keV, respectively. **Top right:** Continuum subtracted Magellanic Cloud Emission Line Survey image of MCSNR J0506−7025 with Hα in red and [SII] in green overlaid with 0.3–0.7 keV contours. **Bottom left:** Same as top-left but for MCSNR J0527−7104. **Bottom right:** Same as top-right but for MCSNR J0527−7104, with blue showing [OIII] and overlaid with 0.7–1.1 keV contours.

Athena X-IFU

The diagnostic potential of Fe L-shell transitions has been discussed often in the literature (e.g., Kahn & Liedahl, 1990). Fe L-shell lines dominate the radiative 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 SNRs, with the Athena mirror providing a spatial resolution comparable to *XMM-Newton,* allowing rigorous spatially resolved spectral analyses of all members of the source class. Such a study would allow us to chart the evolution of the shock-heated Fe plasma properties from early times through to the radiative phase when only the X-ray bright Fe core remains.

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 m^2 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 Athena X-IFU for revealing the detailed plasma properties as well as providing a test of atomic databases.

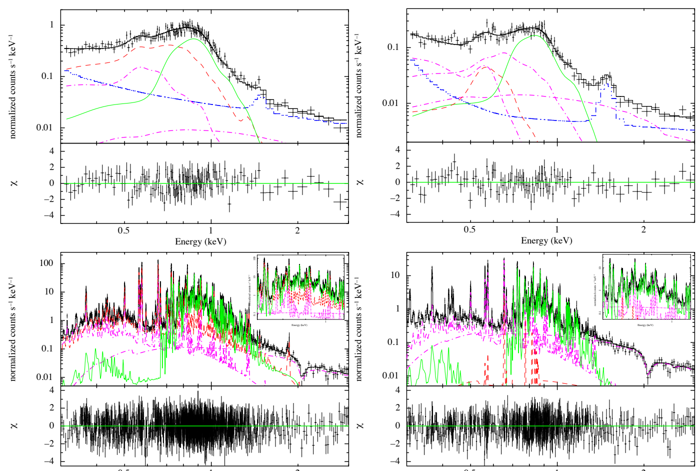

Fig. 2. Top left: EPIC-pn spectrum and best-fit model of MCSNR J0506−7025. The green solid line represents the pure Fe component, the dashed red line shows shell component, the magenta dash-dot lines mark the astrophysical background components, and the blue dash-dot-dot-dot line shows the combined non-X-ray background. **Top right:** Same as top left but for MCSNR J0527−7104 with the dashed red line represents the pure O component in this case. **Bottom left:** Simulated 20 ks Athena X-IFU spectrum of MCSNR J0506−7025. The component colours are the same as in top left. The inset shows a zoom of the 0.7–1.1 keV range. **Bottom right:** Same as bottom left for MCSNR J0527—7104. The component colours are the same as in top right. Note that the X-IFU simulations do not contain a non X-ray background.

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