The XMM-Newton survey of the SMC:
SMP SMC 22 and other planetary nebulae

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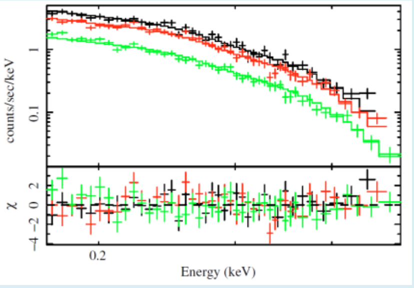
SUMMARY

Planetary nebulae (PNe) are a common stage in the evolution of low and intermediate mass stars, leading to the formation of white dwarfs. They are formed when the fast wind from the central star interacts with the matter of the denser wind previously ejected during the AGB phase. X-ray emission from PNe may originate either in their central star or in the hot gas shocked in the interaction between the two stellar winds.

We present the results of a sensitive search for X-ray emission from planetary nebulae in the Small Magellanic Cloud carried out with XMM-Newton. Significant emission was detected from SMP SMC25 and SMP SMC22, with soft X-ray luminosity of (0.2-6) 10^{35} erg/s and ~10^{37} erg/s, respectively. The X-ray spectrum of SMP 22, which is a bright Super Soft Source, is well fit by a non-LTE model atmosphere composed of H, He, C, N, and O, with abundances equal to those inferred from studies of its nebular lines. The derived effective temperature of 1.5 10^5 K is in close agreement with that found from the optical/UV data and the inferred mass for its central star is about 1 M_o. The exceptionally high X-ray luminosity of SMP 22 is probably due to the high mass of its central star, which is rapidly evolving toward the white dwarf's cooling branch, and to a small amount of intrinsic absorption in the nebula itself.

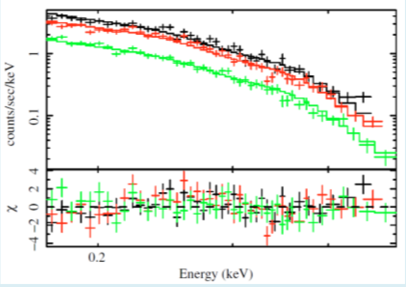
The other SMC PNe have much smaller X-ray luminosities, even if some of them have central stars as hot as SMP 22. Their non detection in our survey s probably caused by the combination of absorption in the nebula and the strong dependence of the flux in the EPIC soft X-ray band on the temperature. For more details, see Mereghetti et al. 2010.

SMP 22 BLACKBODY FIT



EPIC pn spectra in three observations of SMP 22 (at different off-axis agles) fitted with a blackbody model

SMP 22 NLTE ATMOSPHERE FIT



EPIC pn spectra of SMP 22 fitted with NLTE atmosphere with the composition given in the table below

SMP 22: DISCUSSION

SMP 22 is too small (0.71× 0.54 arcsec^2) to be spatially resolved with EPIC, but the soft spectrum and high luminosity we derived imply that its X-ray emission originates in the central star, without any significant contribution from the diffuse gas. The black-body fit implies a bolometric luminosity L_{bol} ~ 8 10^{37} erg/s, while the more realistic atmosphere model with the nebular abundances yields L_{bol} = 6 10^{37} erg/s. This value is orders of magnitude higher than the luminosity that can be produced in the surrounding shock-heated gas.

The good fit provided by our NLTE model supports the interpretation of SMP 22 as a single, very hot star on its way to becoming a relatively massive (~1 M_o) white dwarf. Additional evidence of a high mass star is the high N/O ratio, which is consistent with a type I PN, and indicative of a massive progenitor (see, e.g., Stanghellini 2007).

The temperature of the central star derived from our X-ray spectral analysis (1.5 10^5 K) is in good agreement with the values obtained from the modeling of nebular optical/UV emission lines.
Assuming a black-body spectrum for the ionizing radiation from the central star, Villaver et al. (2004) derived T_{HeII} = (1.222 ± 0.145) 10^5 K and T_H = (0.77 ± 0.18) 10^5 K, using the He II 4686 Å and H_β lines, respectively.
A temperature T = 1.15 10^5 K was instead obtained from IUE spectroscopy, by adopting NLTE model atmospheres (Aller et al. 1987).

Thus a self-consistent picture, in terms of temperature, mass, and radius of the central star can be obtained with a NLTE model atmosphere with the same elemental abundances derived from optical observations of the nebula. The inferred mass for the central star, of the order of 1 M_o, implies that SMP 22 is the descendent of a relatively massive progenitor (see H-R diagram below).
This may explain its exceptional luminosity, as well as the apparent rarity of these objects, which evolve very quickly toward the cooling white dwarf sequence.

SMP 22 X-RAY RESULTS

SMP 22 is a high-excitation planetary nebula with extremely high X-ray luminosity. It was detected in soft X-rays with the Einstein Observatory and ROSAT and included in the class of super-soft X-ray sources (Brown et al. 1994, Kahabka et al 1994). The ROSAT spectrum was fit with a blackbody or LTE white dwarf atmosphere models with H or He compositions. The derived temperatures were of about 4 10^5 K in all cases, but while the blackbody yielded an unrealistic bolometric luminosity of 3 10^{38} erg/s, the atmosphere models gave L_{bol} = 2 10^{37} erg/s (Heise et al. 1994).

Our four XMM-Newton pointings including the position of SMP 22 confirm its high luminosity, lack of variability, and very soft spectrum. Black-body or thermal plasma models give temperatures of about (3−5) 10^5 K and $N_H \approx 5\ 10^{20}$ cm^{-2} (see details in the following table).

Mod.	χ^2_{red}/d.o.f.	N_H (10^{20} cm^{-2})	T (10^5 K)	R (10^9 cm)	α	Z	F_X (10^{-10} $\frac{erg}{cm^2 s}$)	F_{bol} (10^{-10} $\frac{erg}{cm^2 s}$)
Blackbody	0.98/124	$5.2^{+1.3}_{-1.9}$	$3.13^{+0.46}_{-0.23}$	$3.4^{+3.4}_{-2.1}$	–	–	0.9	1.9
Brems.	1.10/124	$4.1^{+5.2}_{-1.0}$	4.87 ± 0.46	–	–	–	0.6	12.3
Mekal	0.93/123	$5.5^{+2.0}_{-1.7}$	3.94 ± 0.69	–	–	$0.02^{+0.02}_{-0.01}$	3.0	86.1
Pow. law	1.69/124	≥4.89	–	–	≥9.4	–	≥22.6	–

We also explored fits with model atmospheres computed under non-local thermodynamic equilibrium (NLTE) conditions, using the Tübingen Model-Atmosphere Package (Werner et al. 2003; Rauch & Deetjen 2003). These models, for a fixed chemical composition, have gravity (log g) and effective temperature (T_{eff}) as free parameters. Adopting a pure H composition, good fits are obtained for T_{eff} = (0.7–1.1) 10^5 K, but with unconstrained values of gravity in the wide range 5 < log g < 9. A Helium atmosphere model gives a good fit with T_{eff} = (1–1.2) 10^5 K, and log g ~ 5.5 ± 0.5.

The best-fit effective temperatures of the H and He NLTE model fits imply that the source emitting radius must be ~1–10 solar radii, to produce the observed source luminosity. However these radii, coupled with their corresponding values of gravity, imply unrealistically high values of mass for the star (>100 M_o). We thus conclude that, although the H and He NLTE model atmospheres provide formally good fits to the EPIC data, they are physically unacceptable.

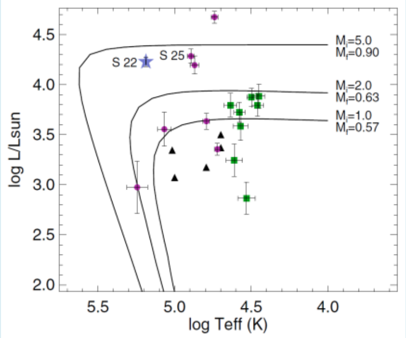
We finally considered a NLTE model atmosphere that includes other elements. Based on the results of optical/UV spectroscopy of the SMP 22 nebular emission, we adopted a model composed of H, He, C, N, and O with abundances fixed to the values determined by Leisy & Dennefeld (1996), and reported in the table below. In all cases, an effective temperature of T_{eff} ~ 1.5 10^5 K is obtained. Although formally the best-fit model is found for log g = 7, the log g = 6 case is preferable because it is only marginally worse but provides more plausible values of mass (~1 M_o) and radius (~0.2 R_o).

Fit parameters for a H/He/C/N/O NLTE atmosphere; F_X is the unabsorbed source flux in the 0.1–0.5 keV energy band.

log g (cm s^{-2})	χ^2_{red}/d.o.f.	N_H (10^{20} cm^{-2})	T (10^5 K)	R (10^{10} cm)	M (10^{33} g)	F_X (10^{-11} $\frac{erg}{cm^2 s}$)	F_{bol} (10^{-10} $\frac{erg}{cm^2 s}$)
6.0	1.17/124	2.8 ± 0.4	1.54 ± 0.01	1.3 ± 0.1	2.4 ± 0.2	2.96	1.51
6.5	1.11/124	$3.2^{+0.3}_{-0.5}$	$1.54^{+0.01}_{-0.02}$	1.5 ± 0.1	10.1 ± 0.6	3.5	2.0
7.0	1.09/124	3.0 ± 0.5	$1.54^{+0.01}_{-0.02}$	1.3 ± 0.1	$25.1^{+2.2}_{-1.3}$	2.73	1.56

	Mass fraction
H	6.808×10^{-1}
He	3.176×10^{-1}
C	9.104×10^{-5}
N	1.061×10^{-3}
O	4.205×10^{-4}

H-R diagram for PN central stars in the SMC



Black triangles are from Aller et al. (1987), purple circles and green squares from Villaver et al. (2004) (Zanstra He and H temperature respectively). The blue star represents the nucleus of SMP 22. Evolutionary tracks for SMC metallicity are from Vassiliadis & Wood (1994)

SMP 22: Discovery of radio emission

The field of SMP 22 was observed with the the Australia Telescope Compact Array (ATCA) on November 30th 2010, with an array configuration 6C, at wavelengths of 3 and 6 cm (9000 and 5500 MHz), and a bandwidth of 2GHz. These observations, taken as part of a campaign to study the bright end of the radio luminosity function of PNe, have provided the first radio detection of SMP 22, which is one of the faintest extragalactic radio PN detected so far.

The observations were carried out in snap-shot mode, totaling about 1 hr of integration over a 12 hr period. PKS B1934-638 was used for flux and bandpass calibration and PKS 0252-712 was used for phase calibration. Standard calibration, editing and imaging techniques were used, but with the large bandwidth multifrequency clean was used to deconvolve the image.

SMP was clearly detected, at more than 5σ, in the 6cm map, with a flux of 0.36 mJy (RMS noise is 0.064 mJy/beam, beam size is 3.167 x 1.999 arcsec) and also visible at 3cm with a flux of 0.31 mJy (RMS noise 0.105 mJy/beam). In both cases the point spread function was fitted to the image. The radio spectral index (S ~ ν^α) is α = -0.28 +/-0.41.

SMP 25 and other PNe in the SMC

Using all the available XMM-Newton data we searched for X-ray emission from all the other catalogued PNe in the SMC. Besides SMP 22, the only other positive detection is SMP SMC 25, also known as LIN357 (Meyssonnier & Azzopardi 1993). This source was already seen with ROSAT (Kahabka et al. 1999), but with a large positional uncertainty which prevented its firm association with the planetary nebula. The EPIC count rate of 3.2+/-0.9 counts/ksec corresponds to a 0.1-1 keV luminosity of 6 10^{35} erg/s, assuming a blackbody spectrum with kT=20 eV or 2 10^{34} erg/s for a a thermal bremsstrahlung with kT = 100 eV (in both cases we assumed N_H = 5 10^{20} cm^{-2}).

The X-ray detection of SMP 22 is unsurprising, because all the optical/UV data indicate that this PN hosts one of the hottest central stars. On the other hand, other SMC PNe with similarly high temperature are at least two orders of magnitude fainter in X-rays (including SMC 25, which has a Zanstra temperature only a factor of two lower than that of SMP 22 (Villaver et al. 2004)).

The X-ray faintness of SMC PNe with hot central stars is probably caused by the combination of absorption in the nebula and the strong dependence of the flux in the EPIC soft X-ray band on the temperature. The small N_H we derived for SMP 22 is consistent with the Galactic value in the SMC direction, and indicative of only little or no intrinsic absorption in the nebula itself.

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