Mem. S.A.It. Suppl. Vol. 5, 276

Memorie della
Supplementi

X-ray Emission Lines in ULXs?

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Abstract. The *XMM* EPIC-pn spectrum of the ultra-luminous X-ray source NGC 1313 X-1 shows evidence for the presence of an Oxygen emission line. Assuming solar composition for the absorbing material along the line of sight, the deviation with respect to the best fitting continuum is statistically significant at about the 4σ level. The simultaneous presence of an excess in emission at other energies, although at a much reduced significance level, in the X-ray spectra of NGC 1313 X-1 and X-2 is suggestive of typical emission lines from young, interacting supernovae or supernova remnants. This fosters the idea that these ULXs are probably embedded in an association of massive stars, in which some supernova event(s) occured in the recent past.

Key words. Black holes — X-rays: individual (NGC 1313 X-1, NGC 1313-X2/MS 0317.7-6647, NGC 1313-X3/SN 1978K) — X-rays: stars

1. Introduction

First detected by *Einstein* but poorly studied until recently, ultra-luminous X-ray sources (ULXs) are defined as off-nuclear point-like sources whose luminosity exceeds the Eddington limit for $1M_\odot$. Of the few hundreds ULXs found in both elliptical or spiral galaxies, some have been identified with very young supernova remnants, background active galactic nuclei (Foschini et al. 2002, Masetti et al. 2003) or X-ray binary systems. A number of ULXs show X-ray spectra consistent with those of Galactic Black Hole binaries. The variability in the X-ray flux suggests that they are X-ray binaries, with either a stellar mass Black Hole having beamed emission or an Intermediate Mass Black Hole (IMBH, $M_{BH} \sim 100 M_\odot$) with isotropic emission. Up to date only three ULXs have an optical counterpart spectroscopically identified and only one appears to be a companion star in a binary sistem (Roberts et al. 2001).

Recently, a number of *XMM-Newton* observations of ULXs have become available. In many cases the statistics is sufficiently good to perform a detailed spectral analysis. The best fit is often obtained with a two-component model: an absorbed multicolor disk

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(MCD)+power-law (PL). The low temperature, $\approx$ 200 – 300 eV, of the soft component has been taken as further evidence for the presence of an IMBH in some ULXs (Miller et al. 2003, 2004; Cropper et al. 2004; Zampieri et al. 2004, hereafter Z04).

Particularly interesting in this respect is the case of the three ULXs hosted in the nearby spiral galaxy NGC 1313. One of them (NGC 1313 X-3) is known to be associated with the interacting supernova SN 1978K (Schlegel et al. 2000). The other two have been quite extensively studied with several X-ray telescopes (Miller et al. 2003, 2004; Z04 and references therein) and, to date, provide some of the best evidence for the presence of a soft component in the X-ray spectrum of ULXs.

Both NGC 1313 X-1 and X-2 are associated with extended optical emission nebulae, a feature common to other ULXs (Pakull & Mirioni 2002). The nebular optical properties are consistent with those of a shock-ionized supernova remnant (SNR), a stellar wind-shocked nebula or diffuse ionized gas. Given the very large diameter ($\geq$ 100 pc) and inferred mechanical energy, they could be the result of several explosive events (multiple SNRs) or be originated by the intense wind of hot stars. On the basis of this, one may conjecture that at least some ULXs belong to young stellar associations, rich in massive stars. In order to foster the link between these sources and sites of active star formation, it would be crucial to detect X-ray emission lines typical of intermediate mass elements produced in the explosive nucleosynthesis of massive stars (O, Si, S, etc.), such as those observed in Galactic SNRs or young interacting supernovae. As discussed in Miller et al. (2004) and Z04, the continuum subtracted *XMM* EPIC-pn spectrum of NGC 1313 X-1 and X-2 shows significant residuals especially in the 0.5–3 keV range. Here we present a thorough analysis of the *XMM* EPIC pn spectrum of the two sources. Particular emphasis is placed on a careful search for the presence of emission lines.

2. A detailed spectral analysis

XMM observed NGC 1313 on October 17, 2000 for a total of $\sim$ 42 ks. The field was centered on the galaxy nucleus and contains the three ULXs hosted in NGC 1313. For details on data reduction we refer to Mucciarelli et al. (2004). Here we report results of spectral fitting of the *XMM* EPIC-pn data only. The best fit with a two-component model is obtained with an absorbed (WABS) MCD+PL (see Mucciarelli et al. 2004, Table 1, and Z04, Table 2, for fit parameters). Residuals suggest the presence of some emission lines in both sources. In order to test for the presence of spectral features, we added, one by one, gaussian components at different energies where residuals show evidence of some excess in emission.

For NGC 1313 X-1, the most significant residual is at 0.59 keV, identified with a high ionization (He-like) Oxygen line. Adding a gaussian component at 0.59 keV, the improvement of the fit with respect to an absorbed MCD+PL model is significant at the 3.9 σ level. The chance probability derived from the F-TEST is 4.7×10^{-5}. Residuals show also an excess of emission at energies of 1.8 (highly ionized Silicon) and 4.7 keV (unidentified), see Figure 1. Adding other two gaussian components for fitting these residuals does not give any further statistical improvement to the fit. Another fit was attempted adding NEI components (NEI: non-equilibrium ionization collisional plasma model, see Borkowski et al. 2001) to the MCD+PL model. The best fit was obtained adding a single NEI component with solar abundance for all elements except Si, that is 10 times overabundant.

A similar analysis was performed also on the EPIC-pn spectrum of NGC 1313 X-2, following the same approach outlined above. Also in this case the spectrum shows some residuals at energies 0.6, 1.8, 2.4 keV, tentatively associated to high ionization states (H- and He-like) of O, S and Ca, but their statistical significance is very low ($< 2\sigma$ for each individual line). By adding two NEI components, the improvement of the fit with respect to an absorbed MCD+PL model is only at the 1.5 σ level. The two NEI component have similar temperatures but different ionization timescales. The abundances of Si and S are 5 times solar. It is interesting to note that the addition of lines in the spectrum of both sources makes the MCD component more significant.

An independent test on the significance of the detection of an O line in the spectrum of NGC 1313 X-1 was performed running a Monte Carlo simulation of the spectrum. Although some fake spectra show an excess at the 0.59 keV energy, no realization gave a detection at a significance level comparable to those found in the data (3.9 σ, see Mucciarelli et al. 2004 for details).

As noted by Miller et al. (2004), in the WABS absorption model the neutral Oxygen absorption edge was located slightly below its natural energy (0.543 keV), creating a false excess at about the same energy that could be erroneously interpreted as an emission line. In order to test the influence of ISM absorption models on the detection of an O line in NGC 1313 X-1, we repeated our analysis using the Tübingen-Boulder absorption model (TBABS; Wilms et al. 2000), that includes a treatment of gas-phase ISM with revised photoionization cross sections and revised abundances (plus the contribution of grain-phase ISM and molecules). The improvement obtained adding a gaussian component at 0.59 keV to a TBABS+MCD+PO continuum is 4.2 σ (chance probability of $1.1{\times}10^{-5}$). The significance of the line remains fairly high even performing a fit in a restricted energy range (0.4–0.8 keV) around the centroid of the gaussian. Fitting the continuum with an absorbed MCD model, the addition of a gaussian component with frozen energy (0.59 keV) and amplitude (0.01 keV) gives an improvement at the 2.9 σ level (chance probability of 2.0×10^{-3}).

3. Discussion and conclusions

The analysis reported in the previous sections confirms the presence of residuals in the X-ray spectrum of NGC 1313 X-1 and X-2, consistent with emission from highly ionized O, Si, S and Ca (plus a yet unidentified line around 4.7 keV in NGC 1313 X-1). Although the statistical evidence for most of these features is rather scarce ($< 2\sigma$), the presence of an Oxygen line in the EPIC-pn spectrum of NGC 1313 X-1 appears to be significant at about 4 σ. Although we are aware that other statistical methods are more trustworthy to test for the detection of spectral lines (Protassov et al. 2002), the present analysis was based on the F-test. For further discussion about the statistical significance of the detection we refer to Mucciarelli et al. (2004).

Excluding possible background contaminations and instrumental calibration uncertainties (Mucciarelli et al. 2004), the lines could be either intrinsic to the source (e.g. formed in the accretion flow powering the X-ray emission) or originate in its close surroundings. At the distance of NGC 1313 ($\sim$ 3.7 Mpc; Tully 1988), an extraction radius of 30″ corresponds to about 500 pc, so, despite the source appears point-like, we are possibly collecting X-ray photons from the diffuse gas which is also responsible for the optical nebular emission. Concerning the first hypothesis, the lack of any detected residual emission in correspondence to the iron complex at 6.4-6.7 keV makes unlikely the possibility that the features are fluorescent lines from an X-ray illuminated accretion disk. The simplest interpretation is that we are observing typical emission features of shock-ionized SNRs. The X-ray lines detected in Galactic SNRs are usually much stronger with typical equivalent widths of $0.3 - 0.6$ keV, but detailed spectral analyses of *Chandra* data show that both the line and continuum components may vary significantly across the remnant (e.g. Cas A, Hughes et al. 2000). The presence of significant amounts of O, Si, S and Ca in the ejecta is expected as a result of explosive nucleosynthesis.

Our tentative conclusion is that the spectral residuals in the *XMM-Newton* EPIC-pn spectrum of NGC 1313 X-1 and X-2 originate in the remnants left over after the explosion of one or more supernovae belonging to the stellar association of massive stars where the two ULXs are probably embedded.

Acknowledgements. This work has been partially supported by the Italian Ministry for Education,

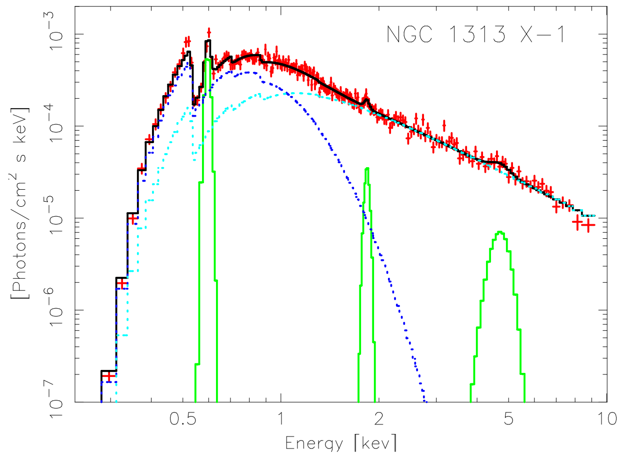

Fig. 1. *XMM* EPIC-pn spectrum of NGC 1313 X-1: absorbed MCD+PL model with three gaussian components at energies 0.59, 1.8 and 4.7 keV.

University and Research (MIUR) under grants COFIN-2002-027145.

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