Black Holes from Stars to Galaxies – Across the Range of Masses
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Chemical abundances of secondary stars in low mass X-ray binaries

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Abstract. Low mass X-ray binaries (LMXBs) offer us an unique opportunity to study the formation processes of compact objects. Secondary stars orbiting around either a black hole or a neutron star could have captured a significant amount of the ejected matter in the supernova explosions that most likely originated the compact objects. The detailed chemical analysis of these companions can provide valuable information on the parameters involved in the supernova explosion such us the mass cut, the amount of fall-back matter, possible mixing processes, and the energy and the symmetry of the explosion. In addition, this analysis can help us to find out the birth place of the binary system. We have measured element abundances of secondary stars in the LMXBs A0620–00, Cen X-4, XTE J1118+480 and Nova Sco 94. We find solar or above solar metalicity for all these systems, what appears to be independent on their locations with respect to the Galactic plane. A comparison of the observed abundances with yields from different supernova explosion together with the kinematic properties of these systems suggest a supernova origin for the compact objects in all of them except for A0620–00, for which a direct collapse cannot be discarded.

Keywords. black hole physics — stars: abundances — stars: evolution — stars: individual (XTE J1118+480, A0620-00, Nova Sco 94, Cen X-4) — stars: neutron — supernovae: general — X-rays: binaries

1. Introduction

A low mass X-ray binary (LMXB) consists of a secondary star orbiting a compact object, either a black hole or a neutron star. An accretion disk forms when the secondary star transfers matter onto the compact object. These accretion processes that take place in the vicinity of the compact object are responsible of X-ray emission of these systems.

A particularly interesting subclass of X-ray binaries are the soft X-ray transients (SXTs), which show recurrent outbursts followed by periods of quiescence lasting several decades, when the stellar radiation dominates over the disk emission in optical and infrared wavelengths. Spectroscopic analysis of SXTs performed at quiescence allows us to study the dynamical and chemical properties of companion stars.

At the beginning of the 90s, this project was initiated after the discovery of a black hole in the X-ray binary V404 Cygni (Casares *et al.* 1992), from the analysis of the radial velocity curve of the secondary star. The inspection of the spectrum of this star also provided the measurement of an unexpectedly high Li abundance (Martín *et al.* 1992), which later on was also found in some other systems (Martín *et al.* 1994a).

Israelian *et al.* (1999) published the chemical analysis of the secondary star in the SXT Nova Scorpii 1994. They intended to search for any possible signature of a supernova (SN) explosion that originated the black hole in this system and found indeed α-elements significantly enhanced in the secondary star. Afterwards, the element abundances were compared with a variety of SN models which brought in new insights on the parameters involved in the explosion (Podsiadlowski *et al.* 2002).

2. Observations and chemical analysis

Spectroscopic observations of the selected sample of SXTs have been carried out using the 8.2 m Very Large Telescope (VLT) with the UV–Visual Echelle Spectrograph (UVES) at a resolving power $\lambda/\delta\lambda \sim 43,000$, except for XTE J1118+480, for which we used the 10-m Keck II telescope equipped with the Echellette Spectrograph and Imager (ESI; Sheinis *et al.* 2002) at medium-resolution ($\lambda/\delta\lambda \sim 6,000$). Individual spectra were corrected from radial velocities and combined to improve the signal-to-noise ratio.

Table 1. Stellar and veiling parameters in SXTs

Parameter	A0620–00	Cen X-4	XTE J1118+480	Nova Sco 94
$T_{\rm eff}$ (K)	4900 ± 150	4500 ± 100	4700 ± 100	6100 ± 200
$\log(g/{\rm cm\ s^2})$	4.2 ± 0.3	3.9 ± 0.3	4.6 ± 0.3	3.7 ± 0.2
[Fe/H]	0.25 ± 0.10	0.4 ± 0.15	0.2 ± 0.2	-0.1 ± 0.1
f_{4500}	0.25 ± 0.05	1.85 ± 0.10	0.85 ± 0.20	0.15 ± 0.05
$m_0/10^{-4}$	-1.4 ± 0.2	-7.1 ± 0.3	-2 ± 1	-1.2 ± 0.3

We obtained the stellar parameters of secondary stars by comparing synthetic spectra with the average spectrum of secondary stars, taking into account the effect of the veiling from the accretion disk on the stellar features (see González Hernández *et al.* 2004, 2005b, 2006 for more details). We selected several spectral features of Fe I and using a grid of LTE models of atmospheres provided by Kurucz (1993) and the LTE code MOOG from Sneden (1973), we generated a grid of synthetic spectra for these features in terms of five free parameters, three to characterize the star atmospheric model (effective temperature, $T_{\rm eff}$, surface gravity, $\log g$, and metalicity, [Fe/H]) and two further parameters to take into account the effect of the accretion disk emission on the stellar spectrum. This was assumed to be a linear function of wavelength and thus characterized by two parameters: veiling at 4500 Å, $f_{4500} = F^{4500}_{\rm disk}/F^{4500}_{\rm cont,star}$, and the slope, m_0.

We compared, using a $\chi2$-minimization procedure, this grid with 1000 realizations of the observed spectrum of these SXTs. Using a bootstrap Monte-Carlo method, we defined the confidence regions for the five free parameters whose most likely values are given in

Table 2. Chemical abundances in SXTs

[X/H]	A0620–00	Cen X-4	XTE J1118+480	Nova Sco 94
Fe	0.14 ± 0.20	0.23 ± 0.10	0.18 ± 0.17	-0.11 ± 0.09
Li*	2.41 ± 0.21	2.98 ± 0.29	< 1.8	< 2.1
Al	0.40 ± 0.12	0.30 ± 0.17	0.60 ± 0.20	0.05 ± 0.18
Ca	0.10 ± 0.20	0.21 ± 0.17	0.15 ± 0.23	-0.02 ± 0.14
Mg	0.40 ± 0.16	0.35 ± 0.17	0.35 ± 0.25	0.69 ± 0.09
Ni	0.27 ± 0.10	0.35 ± 0.17	0.30 ± 0.21	0 ± 0.21
Ti	0.37 ± 0.23	0.40 ± 0.17	–	0.27 ± 0.22
Si	–	–	–	0.58 ± 0.08
O	–	–	–	0.91 ± 0.08
S	–	–	–	0.66 ± 0.11
Na	–	–	–	0.31 ± 0.25

* Li abundance is expressed as: $\log \epsilon({\rm Li})_{\rm NLTE} = \log[N({\rm Li})/N({\rm H})]_{\rm NLTE} + 12$

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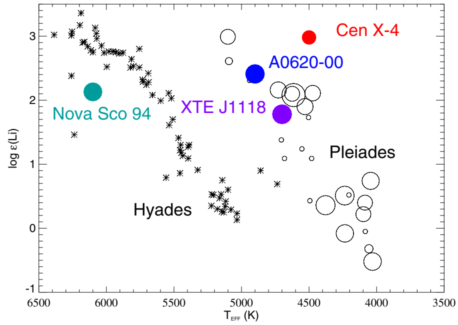

Figure 1. Li abundances of secondary stars in SXTs (filled circles) and rotating Pleiades dwarfs whose age is $\sim 1.2\times10^8$ yr (open circles, García López *et al.* 1994), and Hyades stars whose age is $\sim 7\times10^8$ yr (asterisks, Thorburn *et al.* 1993), versus effective temperature. The sizes of the circles are related to $v\sin i$.

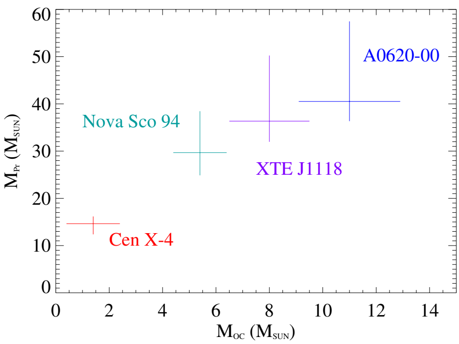

Figure 2. Relationship between the masses of the progenitor star and the compact object in the SXTs of the sample. The size of the crosses indicates the length of the error bars.

Table 1. Average surface gravities were found to be lower than typical values in main sequence stars which indicates that these stars are expanded, filling their Roche lobes.

Using the derived five parameters we analyzed several spectral features of Fe, Li, Mg, Al, Ca, Ti and Ni, except for XTE J1118+480 for which we could not measure the Ti abundance due to the relatively poorer quality of the observed spectrum in the region where the Ti lines are located. In Nova Sco 94 we also measured the element abundances of O, S, Si and Na, using not only the VLT/UVES but also the Keck/HIRES spectrum published by Israelian *et al.* (1999) (see Table 2). These preliminary results of the analysis of the new VLT/UVES data of Nova Sco 94 will be published in González Hernández *et al.* (2007, in preparation).

3. Discussion and conclusions

3.1. *Li abundances in SXTs*

The Li abundances of the secondary stars in the SXTs (see Table 2) of the sample appear to be unexpectedly high in comparison with typical values found in stars with the same spectral type, except for the secondary star of spectral type F in Nova Sco 94. This indicates either that these systems are relatively young ($\lesssim 8\times10^7$ years old, see Fig. 1) and the rotational velocity might have partially inhibited the Li depletion (Maccarone *et al.* 2005), or that there exists a mechanism able to enrich the atmospheres of these stars (see e.g. Martín *et al.* 1994b).

3.2. *Nucleosynthesis in the progenitors of compact objects*

The abundances of *heavy* elements in the secondary stars of SXTs are typically solar or higher than solar abundances (see Table 2), independent of their current locations with respect to the Galactic plane. This might not be expected since two of these systems, namely Cen X-4 (González Hernández *et al.* 2005a) and XTE J1118+480 (Mirabel *et al.*

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2001) are moving in halo regions, and therefore, they abundance pattern could have resembled that of Halo stars and globular cluster stars which are generally metal poor (with heavy elements between 10 and 1000 times less abundant than in the Sun).

Secondary stars in these system could have captured a significant amount of the ejected matter in the supernova explosions that gave rise to the formation of the compact objects in these SXTs. We have compared the observed abundances with the expected abundances from yields of a variety of SN models of different metalicities, progenitor masses, geometries and explosion energies (Umeda & Nomoto 2002, 2005 Tominaga *et al.* 2006, in preparation Maeda *et al.* 2002). Here we summarize the conclusions of these studies:

(i) The strong overabundance of oxygen, sulphur and other alpha-elements and the kinematics support that the black hole in Nova Sco 94 originated in a supernova explosion. However, the relatively low Al abundance is not reproduced by current SN models (see González Hernández *et al.* 2007, in preparation)

(ii) The chemical abundances of A0620-00 could be explained only if the outer layers of the progenitor He core were ejected although a direct collapse cannot be discarded (see González Hernández *et al.* 2004).

(iii) The observed abundances combined with the peculiar kinematics of Cen X-4 and the halo black hole binary XTE J1118+480 support an origin in a supernova explosion. The massive progenitors were most likely born in the Galactic disc. In XTE J1118+480, an asymmetric explosion appears necessary to explain the kinematics and the abundance pattern (see González Hernández *et al.* 2005b, 2006).

(iv) Finally, this analysis could provide a preliminary relationship between the masses of the compact objects and their massive progenitors (see Fig. 2). We shall remark that the abundance analysis together with the comparison with SN models allowed us to estimate the most likely masses of the He core progenitors. However, the free parameter of the fraction of the amount of captured matter by the secondary star produces a degeneracy and it is only possible to establish a lower limit of the masses of the He cores. The upper limit is estimated from the maximum ejected mass which still keep both components of the system gravitationally bound with each other after the SN explosion.

Acknowledgements

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ANDREW KING: Did you consider the idea that the companion was more massive in the past, nuclear-evolved, and then captured by angular momentum losses to a short period? An analysis like this was published by Haswell *et al.* (2003).

JONAY GONZALEZ HERNANDEZ: The important point is if the secondary star was less massive in the past than its massive companion. In that case, considering a secondary star of two solar masses or one solar mass does not change the implications of the abundances measured. Among the parameters we considered in the supernova explosion model, the capture efficiency can be adjusted to reproduce the observed abundances. In this sense, one should compare the result of the pollution by supernova explosion with self-pollution of the secondary if it is an evolved star. To answer this question it is necessary to measure abundances of C, N and O in the secondary star.

FELIX MIRABEL: Comment: Besides the chemistry, the kinematics shows that black holes can be formed in energetic supernova explosions that lead directly to the star death.

JONAY GONZALEZ HERNANDEZ: Kinematics provides additional information on the process of formation of compact objects. However, kinematics alone might not be enough to establish the origin of a compact object. Both the kinematics and the chemical abundances of the secondary star allow us to make stringent constraints on the formation of compact objects.


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