

# Chemical Abundances in the Secondary Star of the Neutron Star Binary Centaurus X-4

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## ABSTRACT

Using a high resolution spectrum of the secondary star in the neutron star binary Cen X-4, we have derived the stellar parameters and veiling caused by the accretion disk in a consistent way. We have used a  $\chi^2$  minimization procedure to explore a grid of 1500 000 LTE synthetic spectra computed for a plausible range of both stellar and veiling parameters. Adopting the best model parameters found, we have determined atmospheric abundances of Fe, Ca, Ti, Ni and Al. These element abundances are super solar ( $[\text{Fe}/\text{H}] = 0.23 \pm 0.10$ ), but only the abundance of Ti and Ni appear to be moderately enhanced ( $\geq 1\sigma$ ) as compared with the average values of stars of similar iron content. These element abundances can be explained if the secondary star captured a significant amount of matter ejected from a spherically symmetric supernova explosion of a  $4 M_{\odot}$  He core progenitor and assuming solar abundances as primordial abundances in the secondary star. The kinematic properties of the system indicate that the neutron star received a natal kick velocity through an aspherical SN and/or an asymmetric neutrino emission. The former scenario might be ruled out since our model computations cannot produce acceptable fits to the observed abundances. We have also examined whether this system could have formed in the Galactic halo, and our simulations show that this possibility seems unlikely. We also report a new determination of the Li abundance consistent with previous studies that is unusually high and close to the cosmic Li abundance in the Galactic disk.

*Subject headings:* stars:neutron—stars:abundances—stars:individual (Cen X-4)—stars:X-rays:low-mass—binaries

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## 1. Introduction

The optical counterpart of the low mass X-ray binary (LMXB) Cen X-4 (V822 Cen) was

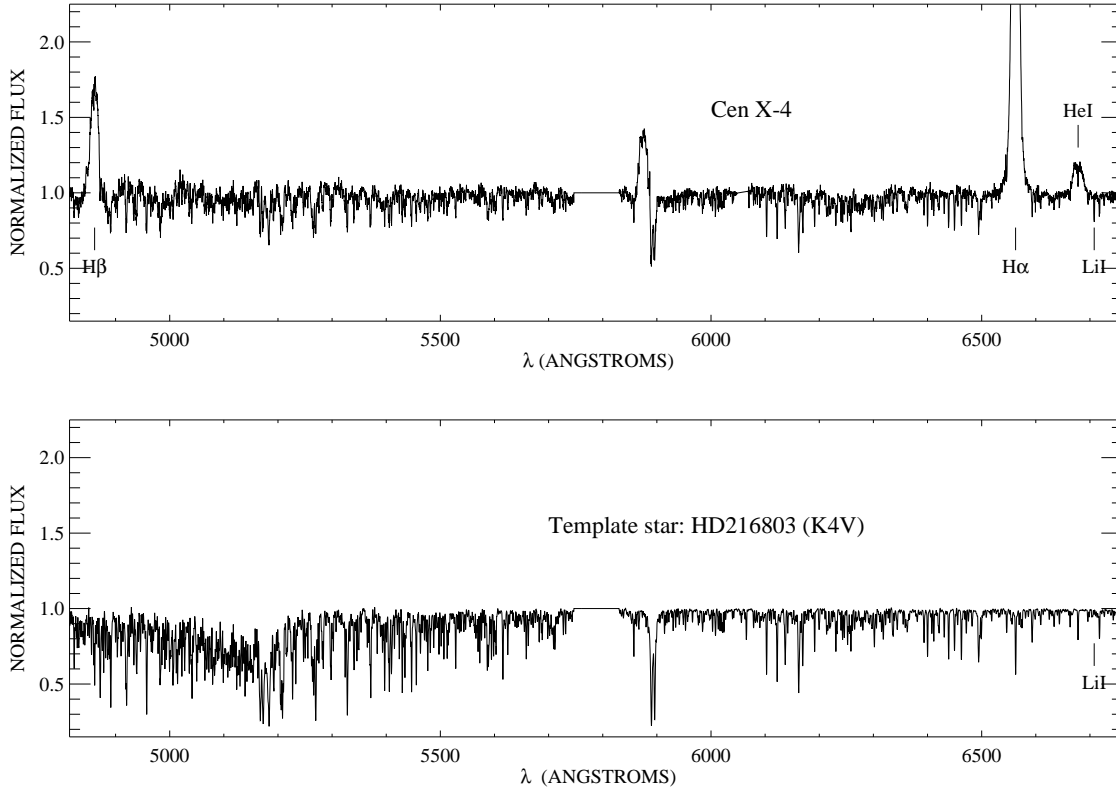


Fig. 1.— Observed spectrum of the secondary star of Cen X-4 (top) and of a properly broadened template (HD 216803, bottom).

firstly identified during an X-ray outburst in 1979 (Kaluzienski et al. 1980), ten years after the X-ray outburst detected by the satellite *Vela 5B* during an X-ray outburst in 1969 (Conner et al. 1969). At that moment, it resembled an  $m_V \sim 13$  magnitude blue star that had increased in brightness by  $\sim 6$  magnitudes from its pre-outburst value (Canizares et al. 1980). About three weeks after the 1979 outburst a type I X-ray burst was observed, which indicated that the X-ray source is a neutron star (Matsuoka et al. 1980). Two weeks later the optical counterpart had faded to  $m_V = 18.2$  mag and spectral observations revealed the presence of a late-type companion star (K3–K7) in the system (van Paradijs et al. 1980). Later optical studies determined the orbital period,  $P = 0.629$  d and a system center-of-mass velocity with respect to the Sun of  $137 \pm 17$  km s $^{-1}$  (McClintock & Remillard 1990). The corresponding mass function was then estimated at  $f(M) = 0.23 M_\odot$ ,

which further supported the argument for a neutron star primary (rather than a black hole, McClintock & Remillard 1990). More recently, from measurements of the orbital inclination and binary mass ratio, the compact object mass has been estimated at  $M_{\text{NS}} = 0.5\text{--}2.1 M_\odot$  (Shahbaz et al. 1993) and the companion star mass, in the range  $0.04 < M_2 < 0.58 M_\odot$  (Torres et al. 2002).

The evolutionary status of this system has been widely discussed in the literature. Whereas Chevalier et al. (1989) and McClintock & Remillard (1990) had suggested a scenario in which the secondary star was a “stripped giant” with a very low mass ( $M_2 \sim 0.1 M_\odot$ ), Shahbaz et al. (1993) favored the case for a subgiant. In both cases the secondary star would be an evolved star that had spent more than 80 per cent of its life (i.e.,  $\sim 10^9\text{--}10^{10}$  yr depending on its initial mass). On the contrary, the compact object in this system is

a neutron star, probably the remnant of the SN explosion of the initial massive component of the binary. The ejected material in the SN explosion is composed of heavy nuclei as products of the hydrostatic and explosive nucleosynthesis in the massive star.

Recent studies of chemical abundances of secondary stars in low mass X-ray binaries have opened up a new window of information on the later stages in the evolution of massive stars. A significant amount of the ejected matter in any supernova explosion that formed the compact objects in these systems could be captured by the companion stars. These stars could therefore show anomalous abundances as signatures of the explosion. Detailed chemical analysis of the atmospheres of the secondary stars could constrain many parameters involved in supernova explosion models, such as the mass cut, the amount of fallback matter, any possible mixing, and explosion energies and geometries. Indeed, the chemical analysis of the secondary stars provides evidence for a supernova event in the history of the systems Nova Sco 94 (Israelian et al. 1999; Brown et al. 2000; Podsiadlowski et al. 2002) and A0620-00 (González Hernández et al. 2004).

In this paper we present the chemical abundance analysis of the secondary star of the LMXB Cen X-4 and discuss these results in the context of possible evolutionary scenarios.

## 2. Observations

We obtained 20 spectra of Cen X-4 with the UV-Visual Echelle Spectrograph (UVES) at the European Southern Observatory (ESO), *Observatorio Cerro Paranal*, using the 8.2 m Very Large Telescope (VLT) on 2000 April 25 and 2000 June 9, covering the spectral regions  $\lambda\lambda 4800\text{--}5800 \text{ \AA}$  and  $\lambda\lambda 5800\text{--}6800 \text{ \AA}$  at resolving power  $\lambda/\delta\lambda \sim 43,000$ . Short exposures (718 s) were chosen in order to minimize possible smearing of spectral lines associated with the radial velocity change during its orbital motion, which we estimated to be less than  $11 \text{ km s}^{-1}$ .

The spectra were reduced in a standard manner using the UVES reduction package within the MIDAS environment. The radial velocity for each spectrum was obtained from the ephemeris reported in Casares et al. (2005, in preparation).

The individual spectra were corrected for radial velocity and combined in order to improve the signal-to-noise ratio. After binning in wavelength in steps of  $0.21 \text{ m\AA}$  the final spectrum had a signal-to-noise ratio of 110 in the continuum. This spectrum is shown in Figure 1.

## 3. Chemical Analysis

### 3.1. Stellar Parameters

The contribution of the emission from the accretion disk to the total flux in Cen X-4 has been estimated at  $\sim 25\text{--}30\%$  and  $40\text{--}50\%$  in the *V* and *B* bands, respectively, whereas it is at least 80% at  $\lambda 3800 \text{ \AA}$  (Chevalier et al. 1989; Torres et al. 2002). As in González Hernández et al. (2004), we have obtained the veiling, together with the stellar atmospheric parameters, using synthetic spectral fits to the high resolution spectrum of the secondary star in Cen X-4. First, moderately strong and relatively unblended lines of several elements of interest were identified in the high resolution solar flux atlas of Kurucz et al. (1984). We selected several spectral features containing in total 29 absorption lines of Fe I with excitation potentials between 0.5 and 4.5 eV. In order to compute synthetic spectra for these features, we adopted the atomic line data from the Vienna Atomic Line Database (VALD, Piskunov et al. 1995) and used a grid of local thermodynamic equilibrium (LTE) models of atmospheres provided by Kurucz (1992, private communication). Synthetic spectra were then computed using the LTE code MOOG (Snedden 1973). To minimize the effects associated with the errors in the transition probabilities of atomic lines, we adjusted the oscillator strengths,  $\log gf$  values of the selected lines until we succeeded in reproducing the solar atlas of Kurucz et al. (1984) with solar abundances (Anders & Grevesse 1989).

We generated a grid of synthetic spectra in terms of five free parameters, three to characterize the star atmospheric model (effective temperature,  $T_{\text{eff}}$ , surface gravity,  $\log g$ , and metallicity,  $[\text{Fe}/\text{H}]$ ), 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  $4500 \text{ \AA}$ ,  $f_{4500} = F_{\text{disk}}^{4500}/F_{\text{sec}}^{4500}$ , and the slope,  $m_0$ . Note that the total flux is defined as  $F_{\text{total}} = F_{\text{disk}} + F_{\text{sec}}$ ,

TABLE 1  
RANGES AND STEPS OF MODEL PARAMETERS

Parameter	Range	Step
$T_{\text{eff}}$	4000 $\rightarrow$ 5500 K	100 K
$\log g$	2.5 $\rightarrow$ 5	0.1
[Fe/H]	-1. $\rightarrow$ 1	0.05
$f_{4500}$	0 $\rightarrow$ 2	0.10
$m_0$	0 $\rightarrow$ -0.00082	-0.00002

TABLE 2  
UNCERTAINTIES IN THE ABUNDANCES OF THE SECONDARY STAR IN CEN X-4

Element	$[E/H]_{\text{LTE}}$	$\Delta\sigma$	$\Delta T_{\text{eff}}$	$\Delta \log g$	$\Delta_{\text{veiling}}$	$\Delta_{\text{TOTAL}}^\dagger$
Al	0.30	0.12	0.05	0.05	0.10	0.17
Ca	0.21	0.07	0.10	-0.12	0.02	0.17
Ti	0.40	0.06	0.13	0.04	0.09	0.17
Fe	0.23	0.09	0.02	0.02	0.03	0.10
Ni	0.35	0.06	0.06	0.02	0.05	0.10
Li*	3.06	0.12	0.10	0.02	0.25	0.29

\*Li abundance is expressed as:

$$\log \epsilon(\text{Li})_{\text{LTE}} = \log[N(\text{Li})/N(\text{H})]_{\text{LTE}} + 12$$

$^\dagger$ The total error was calculated using the following formula:

$$\Delta_{\text{TOTAL}} = \sqrt{\Delta\sigma^2 + \Delta T_{\text{eff}}^2 + \Delta \log g^2 + \Delta_{\text{veiling}}^2}$$

NOTE.—The errors from the dispersion of the best fits to different features,  $\Delta\sigma$ , are estimated using the following formula:  $\Delta\sigma = \sigma/\sqrt{N}$ , where  $\sigma$  is the standard deviation of the measurements. Total errors also take into account the uncertainties associated with the stellar parameters and the veiling.

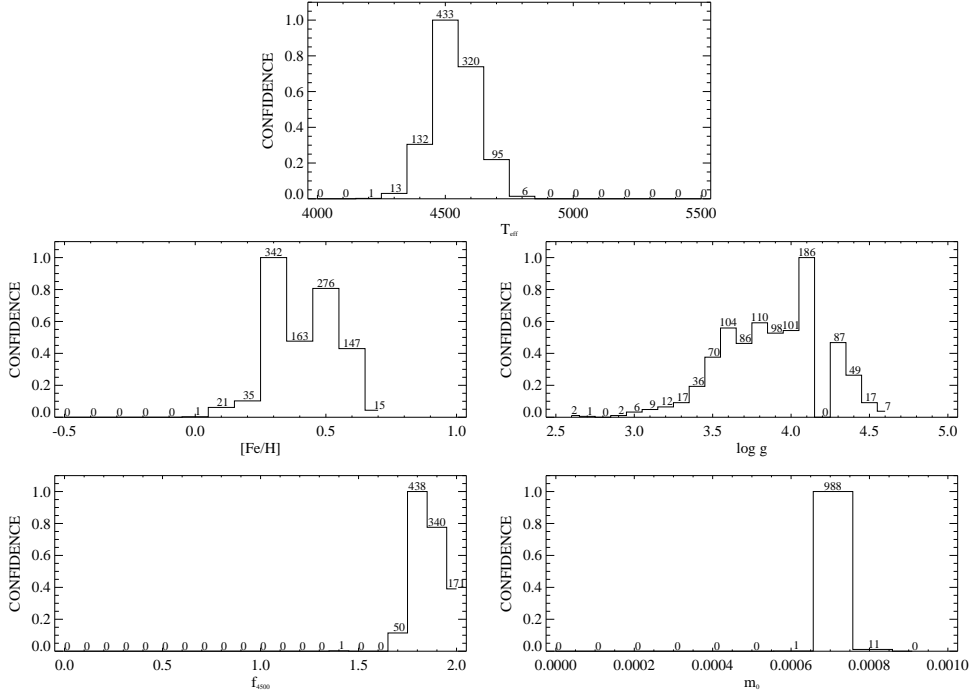


Fig. 2.— Distributions obtained for each parameter using Monte Carlo simulations. The labels at the top of each bin indicate the number of simulations consistent with the bin value. The total number of simulations was 1000.

where  $F_{\text{disk}}$  and  $F_{\text{sec}}$  are the flux contributions of the disk and the continuum of the secondary star, respectively. These five parameters were changed according to the steps and ranges given in Table 1. A rotational broadening of  $44 \text{ km s}^{-1}$ , a limb-darkening  $\epsilon = 0.65$  and a fixed value for the microturbulence,  $\xi = 2 \text{ km s}^{-1}$ , was adopted.

The observed spectrum was compared with each of the 1 500 000 synthetic spectra in the grid via a  $\chi^2$  minimization procedure that provided the best model fit. Using a bootstrap Monte-Carlo method we defined the  $1\sigma$  confidence regions for the five free parameters and established the most likely values:  $T_{\text{eff}} = 4500 \pm 100 \text{ K}$ ,  $\log g = 3.9 \pm 0.3$ ,  $[\text{Fe}/\text{H}] = 0.4 \pm 0.15$ ,  $f_{4500} = 1.85 \pm 0.10$ , and  $m_0 = -0.00071 \pm 0.00003$ . Confidence regions determined using 1000 realizations are shown in Figure 2. This spectroscopic determination of the surface gravity is consistent with derived surface gravities from the mass and radius of the secondary star that lie between  $\log g \sim 3.6$ –4.0.

### 3.2. Stellar Abundances

Using the derived stellar parameters we analyzed several spectral regions where we have identified various lines of Fe, Ca, Al, Ti, Ni, and Li, often blended with Fe lines. Each of these spectral regions was carefully normalized using a late type star template (HD 216803) properly broadened with the rotational profile used for the secondary star in Cen X-4 for comparison. We determined the abundances of these elements by comparing the observed spectrum with a grid of synthetic spectra through a  $\chi^2$  minimization procedure. For these spectral syntheses we modified the element abundances while the stellar parameters and the suitable veiling factor for each spectral region were kept fixed (for further details, see González Hernández et al. 2004).

In Figs 3, 4 and 5 we show several spectral regions where we can see the best model synthesis in comparison with the synthesis using solar abundances. We also analyzed the broadened spectrum of the template late type star and found

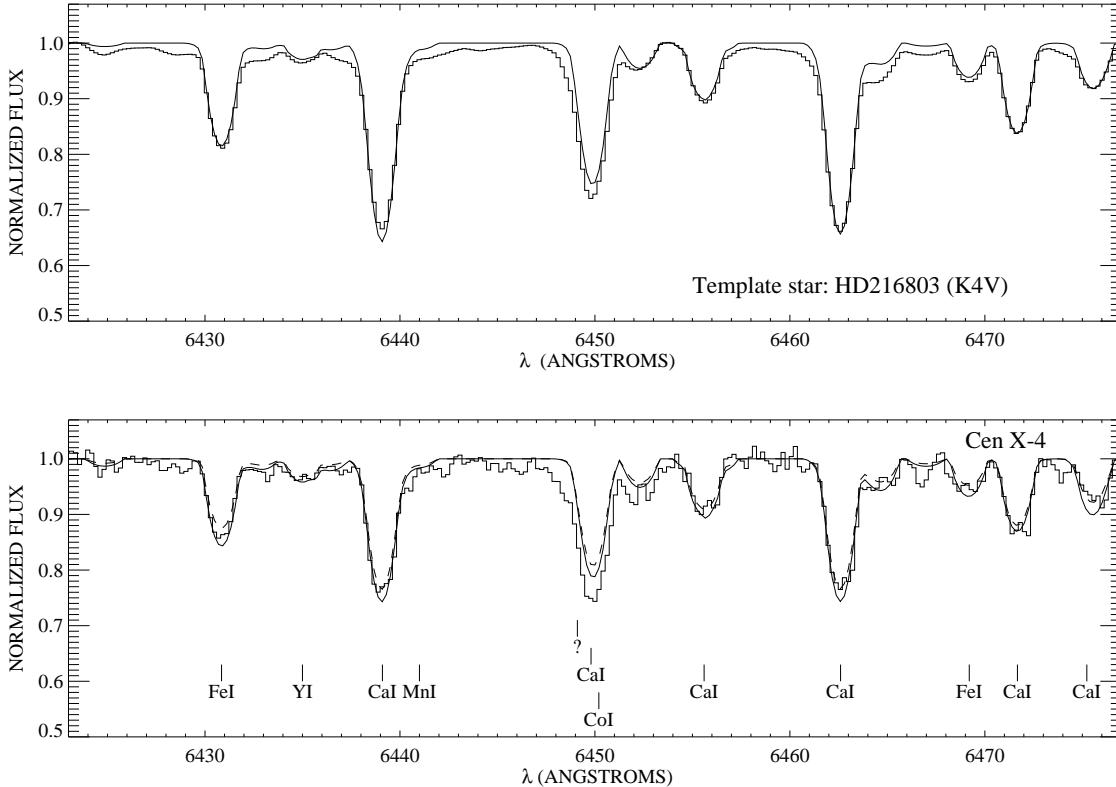


Fig. 3.— Best synthetic spectral fits to the UVES spectrum of the secondary star in the Cen X-4 system (bottom panel) and the same for a template star (properly broadened) shown for comparison (top panel). Synthetic spectra are computed for solar abundances (dashed line) and best fit abundance (solid line).

the abundances of all the elements under study to be close to solar (see Bodaghee et al. 2003) except the Li abundance which was estimated to be  $\log \epsilon(\text{Li}) \lesssim 0.7$ .

Abundances for all the elements are listed in Table 2 and referred to the solar values adopted from Anders & Grevesse (1989). We also give errors,  $\Delta_\sigma$ , estimated from the dispersion of the elemental abundances obtained from the best fits to the various spectral features. Errors associated with uncertainties in effective temperature,  $\Delta_{T_{\text{eff}}}$ , gravity,  $\Delta \log g$ , and veiling,  $\Delta_{\text{veiling}}$ , are also listed in Table 2.

The Li feature is particularly strong in our target resulting in an abundance of  $\log \epsilon(\text{Li})_{\text{LTE}} = 3.06 \pm 0.29$ . We have also estimated the non-LTE abundance correction for this element,

$$\Delta \log \epsilon(\text{Li}) = \log \epsilon(\text{Li})_{\text{NLTE}} - \log \epsilon(\text{Li})_{\text{LTE}}$$

from the theoretical LTE and non-LTE curves of growth in Pavlenko & Magazzù (1996). By using the derived stellar parameters and LTE Li abundance, we obtain  $\log \epsilon(\text{Li})_{\text{NLTE}} = 2.98$  for the secondary star in this system.

The LiI 6708Å resonance doublet may also form in absorption in the atmosphere of the accretion disk during outburst decay (Suleimanov & Rebol 1998). Such lines of Li and possibly of other elements could arise if the disk luminosity is roughly 0.1–0.005 the Eddington luminosity. However, Cen X-4 was observed at quiescence, when its X-ray luminosity was close to  $10^{-6}$  the Eddington luminosity (Asai et al. 1996). In addition, these lines would be extremely broadened as a consequence of the rotation profile of the disk ( $\sim 500$ – $1000 \text{ km s}^{-1}$ ). Therefore, we discard that absorption lines formed in the accretion disk have any

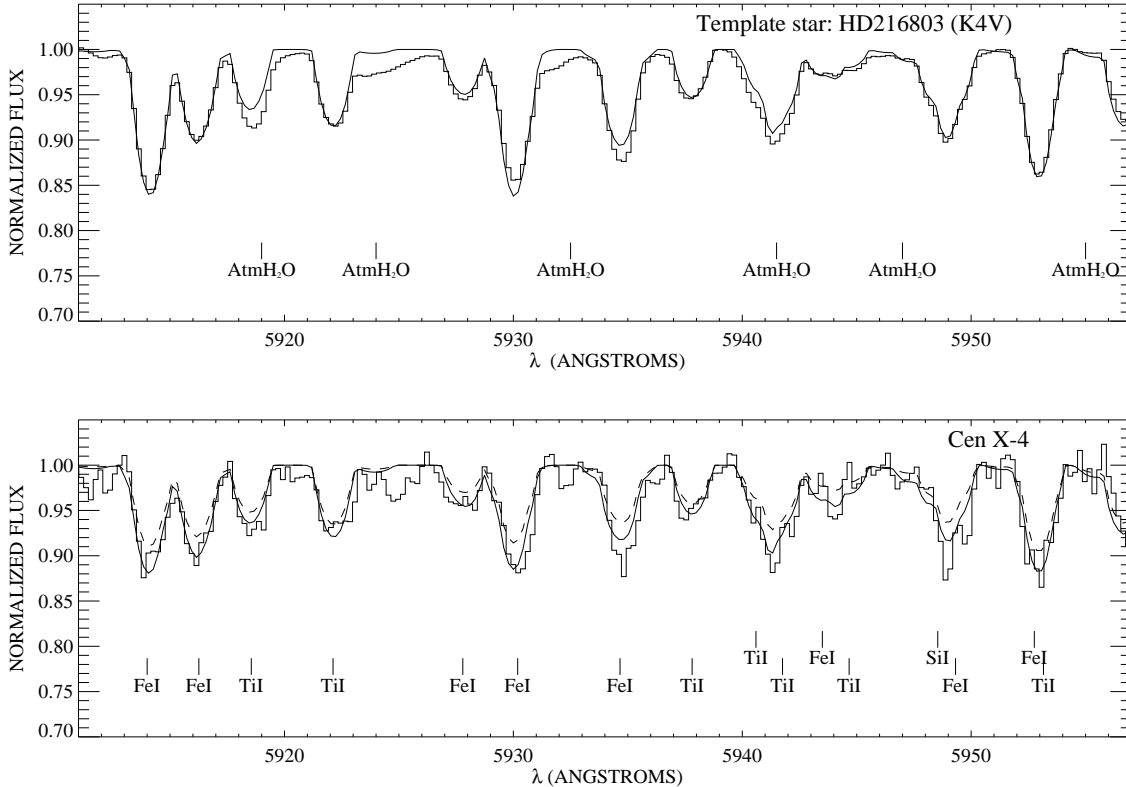


Fig. 4.— The same as in Figure 3. The spectrum of the template is not corrected for telluric lines (atm. H<sub>2</sub>O); therefore, these lines appear broadened in the spectrum (histogram line) and the synthetic spectrum does not fit (solid line).

significant influence on the derived chemical abundances of the secondary star.

In the following section, we will discuss these results in the framework of the origin and evolutionary scenario of the Cen X-4 system.

## 4. Discussion

### 4.1. Heavy Elements

The abundances of *heavy* elements in the secondary star in Cen X-4 are super solar. In Fig. 6 these element abundances relative to iron are shown in comparison with the Galactic abundance trends of these elements in the relevant metallicity range, taken from Feltzing & Gustafsson (1998) and Bodaghee et al. (2003). The error bars in the element abundance ratios ( $[E/Fe]$ , see Table 3) take into account how individual element abun-

dances depend on the various sources of uncertainty when dealing with abundance ratios. The  $[Ca/Fe]$  and  $[Al/Fe]$  ratios of the secondary are consistent with abundances of stars with similar iron content, while Ni and Ti appear to be moderately enhanced. In Table 3 we show the element abundance ratios in the secondary star in Cen X-4 and average values in stars with iron content in the range  $-0.13 < [Fe/H] < 0.33$ , the comparison sample, corresponding to a  $1\sigma$  uncertainty in the iron abundance of the companion star. Whereas  $[Ca/Fe]$  and  $[Al/Fe]$  ratios are consistent with average values, the  $[Ni/Fe]$  and  $[Ti/Fe]$  ratios are  $1\sigma$  higher than the average values of the stars in the comparison sample.

It has been proposed that LMXBs such as Cen X-4 begin their lives as wide binaries and evolve through a common-envelope phase where

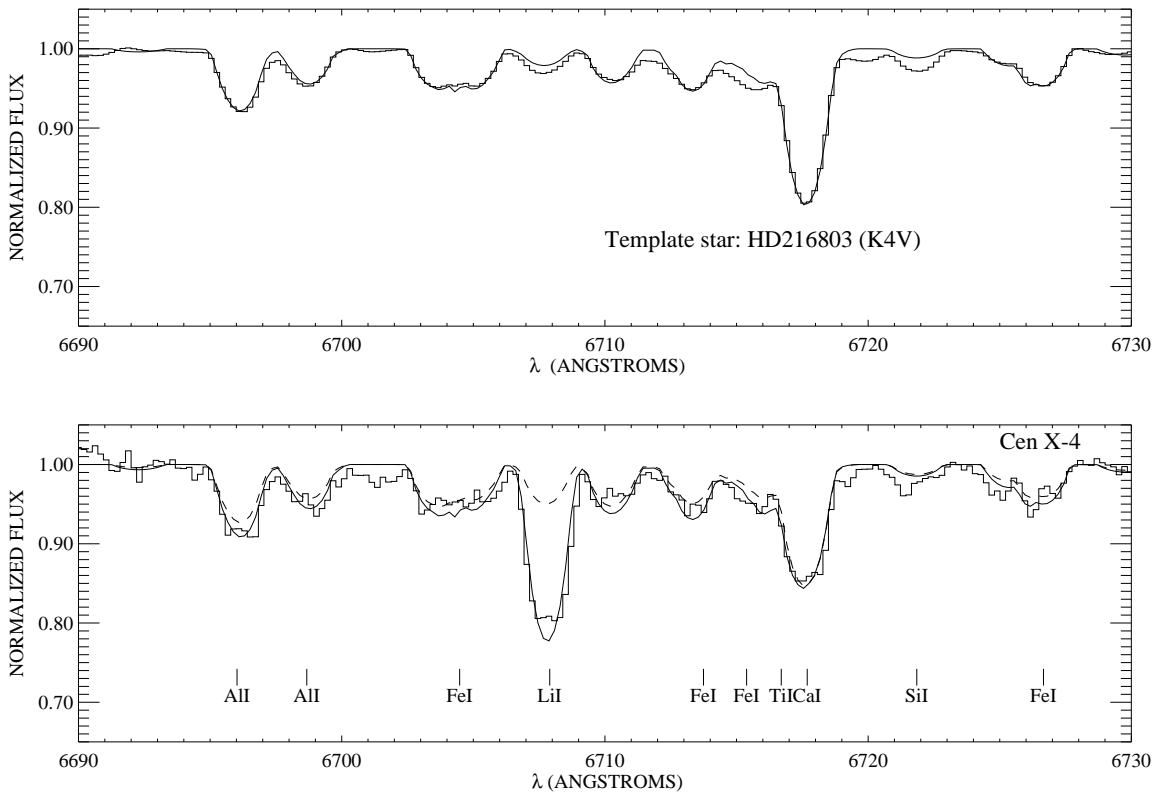


Fig. 5.— The same as in Figure 3.

the companion spirals into the massive star’s envelope (see, for example, Van den Heuvel 1983; de Kool et al. 1987; Nelemans & Van den Heuvel 2001). The helium core of the massive star continues its evolution until dying as a supernova leaving a neutron star or a black hole remnant. Part of the ejected mass in the SN explosion could be captured by the companion star, as has been found in LMXBs like Nova Sco 94 (Israelian et al. 1999) and A0620–00 (González Hernández et al. 2004). We have considered this possibility here in the case of the Cen X-4 system.

#### 4.1.1. Spherical SN explosion

A binary system like Cen X-4 (with neutron star mass  $M_{\text{NS}} = 0.5 - 2.5 M_{\odot}$  and the companion star mass in the range  $M_2 = 0.04-0.58 M_{\odot}$ ) will survive a spherical SN explosion if the ejected mass,  $\Delta M = M_{\text{He}} - M_{\text{NS}} \leq (M_{\text{He}} + M_2)/2$ . Therefore, initial masses for a neutron star and

the secondary star of  $\sim 1.4 M_{\odot}$  and  $\sim 0.8-1 M_{\odot}$  respectively would imply a mass of the He core before the SN explosion  $M_{\text{He}} \leq 3.6-3.8 M_{\odot}$ . Using the expressions given by Portegies Zwart et al. (1997, and references therein), we inferred a mass of the progenitor star,  $M_1 \sim 16 M_{\odot}$ , and a radius  $R_{\text{He}} \sim 0.8 R_{\odot}$  for the helium core. As in González Hernández et al. (2004), we can also estimate the amount of the ejected material in a spherical explosion that could be captured by the companion as coming from a central point since the pre-SN orbital separation between the binary components would be  $a_0 \sim 1.6-2 R_{\odot}$  (assuming  $M_{\text{He}} \sim 4 M_{\odot}$ ,  $M_{\text{NS}} \sim 1.5 M_{\odot}$  and  $M_2 \sim 0.5-0.8 M_{\odot}$ ). The explosion of such a massive primary would have taken place only  $\sim 7 \times 10^6$  yr after the formation of the system (Brunish & Truran 1982). At that time, the radius of an  $0.8 M_{\odot}$  secondary star would be  $\sim 1.2 R_{\odot}$  (D’Antona & Mazzitelli 1994). If we consider a spherically symmetric supernova explosion, taking into account



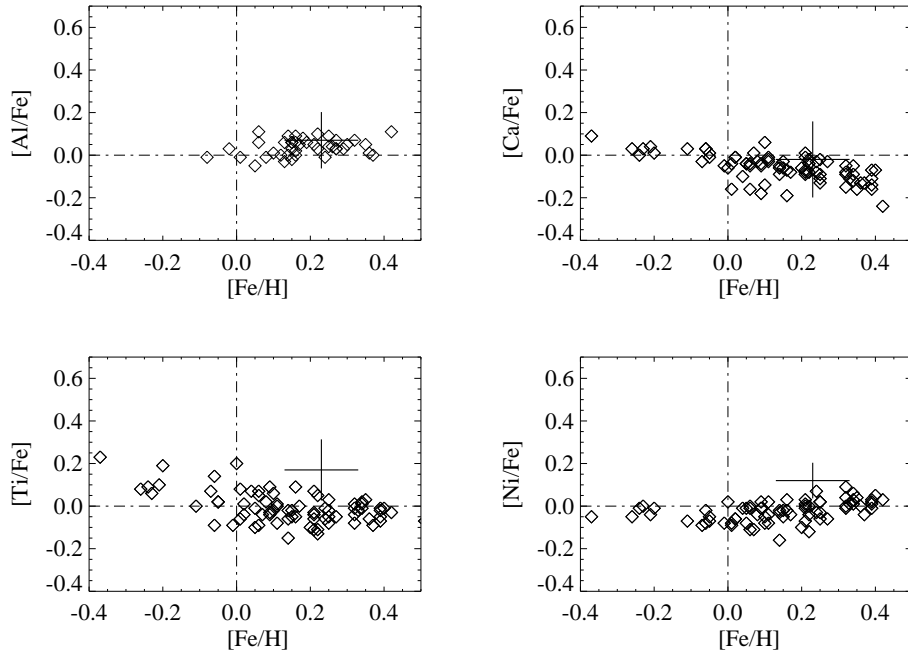


Fig. 6.— Abundances of the secondary star in Cen X-4 (wide crosses) in comparison with the abundances in G and K metal-rich dwarf stars. Galactic trends of Ca, Ni, and Ti were taken from Bodaghee et al. (2003) while Al from Feltzing & Gustafsson (1998). The size of the cross indicates the size of error. The dashed-dotted lines indicate solar abundance values.

the fraction of solid angle subtended by the companion and assuming different capture efficiency factors,  $f_{\text{capture}}$ , the amount of mass deposited on the secondary can be computed as

$$m_{\text{add}} = \Delta M (\pi R_2^2 / 4\pi a_0^2) f_{\text{capture}}$$

In Table 4 we present the expected abundances in the atmosphere of the secondary star after contamination from the progenitor of the compact object for two plausible secondary masses ( $0.8 M_{\odot}$  and  $0.5 M_{\odot}$ ) at the time of the explosion of the primary. We have used a spherically symmetric core-collapse explosion model of He core of mass  $M_{\text{He}} \sim 4 M_{\odot}$  and explosion energy of  $\epsilon = 10^{51}$  ergs. This energy is deposited promptly in the central region of the progenitor core to generate a strong shock wave. The subsequent propagation of the shock wave is followed through a two-dimensional hydrodynamical code, as has been done for aspherical explosion models by Maeda et al. (2002). Nucleosynthesis is solved by detailed nuclear reaction network calculations including 222 isotopes, from

$^1\text{H}$  up to  $^{71}\text{Ge}$ . In the simulations, the directional distribution of the input energy at the mass cut is given in a parametric way to allow asymmetric explosions. One half of the energy is deposited as kinetic energy, and the corresponding initial velocities ( $v_r, v_z$ ) are imposed as  $v_z = \alpha z$  and  $v_r = \beta r$  (here  $r$  is the equatorial direction,  $z$  the jet direction, and  $v_r$  and  $v_z$  the initially imposed velocity components along each direction). Therefore, the initially imposed velocity is a factor of  $\alpha/\beta$  larger in the jet direction than in the equatorial direction. In the spherical symmetric model, the ratio  $\alpha/\beta$  is set to be unity, therefore the model is similar to canonical 1D explosion calculations (see, e.g., Umeda et al. 2000). The details of our explosion calculations can be found in Maeda et al. (2002). Our present models are basically the same as their models, except for the progenitor’s mass and the explosion energy. In our modeling, we have chosen different capture efficiency factors,  $f_{\text{capture}}$ , between 0 and 1. However, simulations of type Ia SNe suggest that the SN blast wave may

TABLE 3

ELEMENT ABUNDANCE RATIOS IN THE SECONDARY STAR IN CEN X-4 AND IN THE COMPARISON SAMPLE

Element	$[E/Fe]_{\text{CenX-4}}$	$\Delta_{[E/Fe], \text{CenX-4}}^*$	$[E/Fe]_{\text{stars}}$	$\sigma_{\text{stars}}$	$\Delta_{\sigma, \text{stars}}$
Al	0.07	0.13	0.04	0.03	0.006
Ca	-0.02	0.18	-0.07	0.04	0.008
Ti	0.17	0.14	-0.04	0.06	0.010
Ni	0.12	0.08	-0.02	0.05	0.010

\*Errors in the element abundance ratios ( $[E/Fe]$ ) in the secondary star in Cen X-4.

NOTE.— $[E/Fe]_{\text{stars}}$  indicates the average values calculated for stars with iron content in the range  $-0.13$  to  $0.33$  corresponding to  $1\sigma$  in the  $[Fe/H]$  abundance of the secondary star in Cen X-4. Ca, Ti and Ni for the comparison sample have been taken from 29 stars in Bodaghee et al. (2003) while Al from 28 stars in Feltzing & Gustafsson (1998). The uncertainty in the average value of element abundance ratios in the comparison sample is obtained as  $\Delta_{\sigma, \text{stars}} = \sigma_{\text{stars}}/\sqrt{N}$  where  $\sigma_{\text{stars}}$  is the standard deviation of the measurements and  $N$ , the number of stars.

induce mass-loss in the secondary instead of matter accretion (Marietta et al. 2000) and therefore, high values for the capture efficiency may not be appropriated. We also assume that the matter captured is well-mixed in the convective envelope of the companion star. The mass of the convective zone of the secondary star was fixed at  $m_{\text{conv}} = 0.5$  and  $0.6 M_{\odot}$  from the evolutionary tracks for a  $0.5$  and  $0.8 M_{\odot}$  secondary star, respectively, with an age of  $\sim 7 \times 10^6$  yr (D’Antona & Mazzitelli 1994).

The mass cut,  $M_{\text{cut}}$ , that divides the ejecta from the collapsing core, is low enough for a significant fraction of iron to be ejected and consequently captured by the secondary star. The secondary star could therefore have had an initial iron abundance lower than its current observed abundance. In order to check this possibility we have assumed different initial metallicities for the secondary and primary star in the system, including low metallicities (given the high galactic latitude,  $b \sim 24^{\circ}$ , of the system that might suggest a halo origin). We have taken the initial element abundances from the galactic trends (Allende Prieto et al. 2004; Stephens & Boesgaard 2002) for four given iron abundances. We have used nucleosynthetic products of the solar metallicity explosion model since the abundance pattern of  $\alpha$ -nuclei can be similar to the solar abundance (Umeda et al. 2000). However, the odd  $Z$  to even  $Z$  element ratios become smaller for lower metallicity, and hence we have excluded  $^{27}\text{Al}$  from low metallicity models.

The expected abundances for the solar abun-

dance model presented in Table 4 can fit very well with the observed abundances in the secondary star for lower mass cuts. However, these element abundances are strongly sensitive to the mass cut, and therefore for a slightly higher value of this parameter the expected abundances cannot reproduce the observed abundances. This strong dependence on the mass cut makes the low metallicity models unable to produce acceptable fits to the observed abundances. In addition, note that for lower metallicity models the secondary star needs to capture 10–20 per cent of the mass in its convective zone from the ejecta (i.e., an  $f_{\text{capture}} \sim 0.2$ – $0.7$ ) to achieve the current observed abundances. Whereas for the solar abundance model by capturing roughly 5% of its convective envelope mass the secondary star can increase sufficiently its element abundances (i.e., an  $f_{\text{capture}} \sim 0.1$ – $0.3$ ). According to the chemical abundance pattern in the secondary star, we find as very unlikely a halo origin. Although, strictly speaking, we may only rule out an origin in the metal-weak halo. The halo is also populated by stars that have been accreted from Milky Way satellites and some of these are of high metallicity. The only known satellites that are accreting onto the Milky Way and comprise a population as metal-rich as the Cen X-4 system are Sagittarius (Ibata et al. 1994, Bonifacio et al. 2004) and Canis Major (Martin et al. 2004, Sbordone et al. 2004). Sagittarius is in a polar orbit (Ibata et al. 1997) and Canis Major in an equatorial orbit (Martin et al. 2004). The present orbit of Cen X-4 (see González Hernández et al. 2005) is

TABLE 4  
SPHERICAL SUPERNOVA EXPLOSION IN CEN X-4

ELEMENT	[E/H] OBS. <sup>a</sup>	[E/H] SAMPLE <sup>b</sup>	[E/H] <sub>†,i</sub> <sup>c</sup>	[E/H] EXPECTED <sup>d</sup>			
				$M_2 = 0.5 M_\odot$		$M_2 = 0.8 M_\odot$	
				$M_{\text{cut}}(M_\odot)$		$M_{\text{cut}}(M_\odot)$	
	1.49	1.55	1.49	1.55			
[Fe/H] <sub>†,i</sub> = 0							
Al	0.30	0.25	0	0.27	0.47	0.27	0.48
Ca	0.21	0.15	0	0.23	0.37	0.23	0.38
Ti	0.40	0.18	0	0.48	0.19	0.49	0.20
Fe	0.23	0.23	0	0.23	0.23	0.23	0.23
Ni	0.35	0.20	0	0.32	0.18	0.32	0.19
[Fe/H] <sub>†,i</sub> = -0.4							
Al	0.30	0.25	...	...	...	...	...
Ca	0.21	0.15	-0.24	0.26	0.49	0.27	0.49
Ti	0.40	0.18	-0.11	0.65	0.26	0.66	0.26
Fe	0.23	0.23	-0.38	0.23	0.23	0.23	0.23
Ni	0.35	0.20	-0.31	0.39	0.17	0.39	0.17
[Fe/H] <sub>†,i</sub> = -0.8							
Al	0.30	0.25	...	...	...	...	...
Ca	0.21	0.15	-0.71	0.24	0.50	0.23	0.51
Ti	0.40	0.18	-0.63	0.67	0.17	0.67	0.17
Fe	0.23	0.23	-0.78	0.23	0.23	0.23	0.23
Ni	0.35	0.20	-0.65	0.41	0.14	0.41	0.15
[Fe/H] <sub>†,i</sub> = -1.4							
Al	0.30	0.25	...	...	...	...	...
Ca	0.21	0.15	-1.17	0.23	0.52	0.52	0.52
Ti	0.40	0.18	-1.16	0.69	0.15	0.15	0.16
Fe	0.23	0.23	-1.41	0.23	0.23	0.23	0.23
Ni	0.35	0.20	-1.12	0.42	0.13	0.13	0.13

<sup>a</sup>Observed abundances of the secondary star in Cen X-4.

<sup>b</sup>Average abundances in stars of the comparison sample (see also Table 4).

<sup>c</sup>Initial abundances assumed for the secondary star in Cen X-4 from Allende Prieto et al. (2004) and Stephens & Boesgaard (2002)

<sup>d</sup>Expected abundances of the secondary star

NOTE.—Expected abundances in the secondary atmosphere contaminated with nucleosynthetic products of a  $16 M_\odot$  *spherically* symmetric core-collapse explosion model ( $M_{\text{He}} \sim 4 M_\odot$ ) for two different secondary masses,  $M_2$ .  $M_{\text{cut}}$  is the mass cut assumed for each model.  $[\text{Fe}/\text{H}]_{\dagger,i}$  is the initial metallicity of the secondary star. The capture efficiency,  $f_{\text{capture}}$ , has been modified in each model until matching the expected with the observed iron abundance. Therefore, the mass captured by the companion,  $m_{\text{add}}$ , lies between 0.02 ( $f_{\text{capture}} = 0.1$ ) and 0.11 ( $f_{\text{capture}} = 0.5$ ) for the extreme values of  $M_2 = 0.5 M_\odot$ ,  $M_{\text{cut}} = 1.49 M_\odot$  and  $[\text{Fe}/\text{H}]_{\dagger,i} = 0$ , and  $M_2 = 0.8 M_\odot$ ,  $M_{\text{cut}} = 1.55 M_\odot$  and  $[\text{Fe}/\text{H}]_{\dagger,i} = -1.4$

not compatible with that of either of these galaxies, thus it seems likely that Cen X-4 originated in neither of them, but a detailed kinematic study is needed to reject this possibility.

#### 4.1.2. Aspherical SN explosion

So far we have been considering a spherically symmetric SN explosion, but the kinematic properties of this system might suggest an aspherical SN explosion, as has been proposed for Nova Sco 94 (Brown et al. 2000). The maximum ejected mass in a spherical SN explosion,  $\Delta M \sim 2.4 M_{\odot}$ , leads to a system velocity of  $\sim 139 \text{ km s}^{-1}$ . González Hernández et al. (2005) measured the proper motion of the system and derived a space velocity of  $v_{\text{sys}} \gtrsim 300 \text{ km s}^{-1}$ , i.e., considerably larger than what could be acquired in the case of a spherical SN explosion. In addition, the Galactic space velocity components ( $U, V, W$ ) of the system are significantly different from the mean values that characterize the kinematics of stars belonging to the thin and the thick disks of the Galaxy. We conclude that the nascent neutron star must have received an additional *kick*, most probably at birth. Theorists have been trying to explain these kicks, whose physical origin remains unclear (see Lai et al. 2001 for a review, and references therein). A *natal* kick could be generated by an asymmetric explosion due to global hydrodynamic perturbations in the supernova core, or it could be a result of asymmetric neutrino emission in the presence of superstrong magnetic fields ( $B \gtrsim 10^{15} \text{ G}$ ) in the proto-neutron star and/or non-standard  $\nu$  physics. In the latter cases, an asymmetry of  $\sim 1\%$  in the neutrino emission is sufficient to account for a kick of  $300 \text{ km s}^{-1}$ ; therefore, a non-spherically symmetric SN explosion is not necessary. Recently, some authors have started to explore the asymmetric-collapse kick mechanisms from global hydrodynamic perturbations. Two and three dimensional studies predict strong neutron star kicks from this mechanism (Burrows & Hayes 1996; Janka et al. 2004) even in excess of  $1000 \text{ km/s}$ . On the contrary, Fryer (2004), on the basis of three dimensional supernova simulations, found that even the most extreme asymmetric collapses do not produced final neutron star velocities above  $200 \text{ km s}^{-1}$ . Therefore, an aspherical SN explosion cannot be ruled out and might be the explanation for the high

space velocity of the system.

Nucleosynthesis in aspherical explosions has been examined by Maeda et al. (2002), who showed that the chemical composition of the ejecta is strongly dependent on direction. In particular, the main effect of the asphericity is that elements produced by the strong  $\alpha$ -rich freeze-out are greatly enhanced relative to iron (e.g.,  $[\text{Ti}/\text{Fe}]$ ). This effect is more pronounced in the jet direction, where the kinetic energy is higher. Therefore, assuming that the jet is perpendicular to the orbital plane, i.e., that the secondary star is located in the equatorial plane of the helium star, elements like Ti, Ni, and Fe are mainly ejected in the jet direction, while Al, O, Si, S, and Mg are preferentially ejected near the equatorial plane. Consequently, we should have found a high Al abundance in the companion star in comparison with the other elements studied but this is not the case. To compare these effects with our observations of Cen X-4 quantitatively, we compute an aspherical explosion of a  $4M_{\odot}$  He core with the explosion energy  $10^{51}$  ergs. The asphericity is induced by the parametric way (see §4.1.1) with the asphericity parameter  $\alpha/\beta = 2$ , i.e., the initial shock velocity at the mass cut is 2 times larger along the jet direction than in the equatorial direction. In table 5 we show the expected element abundances in the secondary star after pollution from the ejecta of an aspherical SN explosion of a  $4 M_{\odot}$  He core. Contrary to the spherical case, Al is dramatically enhanced in all the model computations and this effect is even stronger for higher mass cuts. Therefore, for the solar abundance model, none of the model computations produces acceptable fits, even for lower mass cuts. Note that explosive burning in aspherical SN is weak, ejecting little Ti and Ni, in the equatorial direction. Thus, the mass cut appropriate to the system, i.e.,  $\sim 1.4 M_{\odot}$ , is not deep enough to eject these elements to explain the large values of  $[(\text{Ti}, \text{Ni})/\text{H}]$  observed. The mass cut in the aspherical case is placed at relatively weak burning region as compared with the spherical model. Therefore, the dependence of the model abundance on changing the mass cut is different from the spherical model, which also makes the aspherical model difficult to fit the observed abundances.

Note that all the above results of the aspherical explosion rely on the assumption that the jet di-

TABLE 5  
ASPHERICAL SUPERNOVA EXPLOSION IN CEN X-4

ELEMENT	[E/H] OBS. <sup>a</sup>	[E/H] SAMPLE <sup>b</sup>	[E/H] <sub>†,i</sub> <sup>c</sup>	[E/H] EXPECTED <sup>d</sup>			
				$M_2 = 0.5 M_\odot$		$M_2 = 0.8 M_\odot$	
				$M_{\text{cut}} (M_\odot)$		$M_{\text{cut}} (M_\odot)$	
				1.49	1.55	1.49	1.55
[Fe/H] <sub>†,i</sub> = 0							
Al	0.30	0.25	0	0.59	0.84	0.59	0.84
Ca	0.21	0.15	0	0.43	0.24	0.43	0.24
Ti	0.40	0.18	0	0.21	0.20	0.21	0.20
Fe	0.23	0.23	0	0.23	0.23	0.23	0.23
Ni	0.35	0.20	0	0.18	0.22	0.18	0.22
[Fe/H] <sub>†,i</sub> = -0.4							
Al	0.30	0.25	...	...	...	...	...
Ca	0.21	0.15	-0.24	0.56	0.28	0.56	0.28
Ti	0.40	0.18	-0.11	0.28	0.26	0.28	0.26
Fe	0.23	0.23	-0.38	0.23	0.23	0.23	0.23
Ni	0.35	0.20	-0.31	0.15	0.22	0.15	0.22
[Fe/H] <sub>†,i</sub> = -0.8							
Al	0.30	0.25	...	...	...	...	...
Ca	0.21	0.15	-0.71	0.59	0.25	0.59	0.25
Ti	0.40	0.18	-0.63	0.20	0.17	0.20	0.17
Fe	0.23	0.23	-0.78	0.23	0.23	0.23	0.23
Ni	0.35	0.20	-0.65	0.12	0.21	0.12	0.21
[Fe/H] <sub>†,i</sub> = -1.4							
Al	0.30	0.25	...	...	...	...	...
Ca	0.21	0.15	-1.17	0.61	0.25	0.61	0.25
Ti	0.40	0.18	-1.16	0.19	0.15	0.19	0.15
Fe	0.23	0.23	-1.41	0.23	0.23	0.23	0.23
Ni	0.35	0.20	-1.12	0.11	0.20	0.11	0.20

<sup>a</sup>Observed abundances of the secondary star in Cen X-4.

<sup>b</sup>Average abundances in stars of the comparison sample (see also Table 4).

<sup>c</sup>Initial abundances assumed for the secondary star in Cen X-4 from Allende Prieto et al. (2004) and Stephens & Boesgaard (2002)

<sup>d</sup>Expected abundances of the secondary star

NOTE.—Expected abundances in the secondary atmosphere contaminated with nucleosynthetic products of a  $16 M_\odot$  *non-spherically* symmetric core-collapse explosion model ( $M_{\text{He}} \sim 4 M_\odot$ ) for two different secondary masses,  $M_2$ .  $M_{\text{cut}}$  is the mass cut assumed for each model.  $[\text{Fe}/\text{H}]_{\dagger,i}$  is the initial metallicity of the secondary star. The capture efficiency,  $f_{\text{capture}}$ , has been modified in each model until matching that expected with the observed iron abundance. Therefore, the mass captured by the companion,  $m_{\text{add}}$ , lies between 0.04 ( $f_{\text{capture}} = 0.2$ ) and 0.22 ( $f_{\text{capture}} = 0.8$ ) for the extreme values of  $M_2 = 0.5 M_\odot$ ,  $M_{\text{cut}} = 1.49 M_\odot$  and  $[\text{Fe}/\text{H}]_{\dagger,i} = 0$ , and  $M_2 = 0.8 M_\odot$ ,  $M_{\text{cut}} = 1.55 M_\odot$  and  $[\text{Fe}/\text{H}]_{\dagger,i} = -1.4$

rection is perpendicular to the orbital plane, therefore to the equatorial direction of the progenitor star since the star may well co-rotate with the binary orbit. The assumption that the jet is almost perpendicular to the equatorial direction is justified because recent core-collapse theories suggest the jets, if formed, propagate along the progenitor’s rotational axis (e.g., Fryer & Warren 2004 and references therein). This is also supported by a *Hubble Space Telescope* image of SN 1987A (Wang et al. 2002). The ejecta of SN 1987A is elongated toward the direction perpendicular to the innermost circumstellar ring, which is probably along the equatorial direction (e.g., Chevalier & Dwarkadas 1995).

In the case of low initial metallicity of the secondary star, higher values for the capture efficiency (i.e.,  $f_{\text{capture}} \sim 0.3\text{--}1$ ) are required to achieve the observed Fe abundance since this element is mainly ejected perpendicularly to the orbital plane. Despite this requirement, these simulations cannot fit the observed abundances even for high mass cuts.

In summary, a spherically symmetric SN explosion of a  $4 M_{\odot}$  He core leaving an NS gives a better fit than an aspherical model. A relatively low primary star ( $M_1 \lesssim 20 M_{\odot}$ ) seems to leave an NS and to explode as a normal SN (with an energy of  $\varepsilon = 10^{51}$  ergs, e.g., Nomoto et al. 2003). Our result would suggest that a normal SN would be less aspherical than a hypernova, as proposed for the black hole in the LMXB Nova Sco 94 (Brown et al. 2000). However, we cannot rule out that the companion star did not capture a significant amount of matter from the ejecta of a SN explosion, and therefore that the observed abundances correspond to its primordial abundances.

#### 4.2. Li abundance

The companion star has an unexpectedly high  ${}^7\text{Li}$  abundance close to the cosmic value in the Galactic disk (Martín et al. 1994a), substantially higher than field late-type main sequence stars of similar mass. Convective mixing during pre-main sequence and main sequence evolution is expected to produce significant lithium depletion in the atmospheres of such stars (see Fig. 7), thus a possible explanation for the Li over-abundance in the secondary is that the Cen X-4 system is younger than the Pleiades cluster whose age is  $\sim 120$  Myr

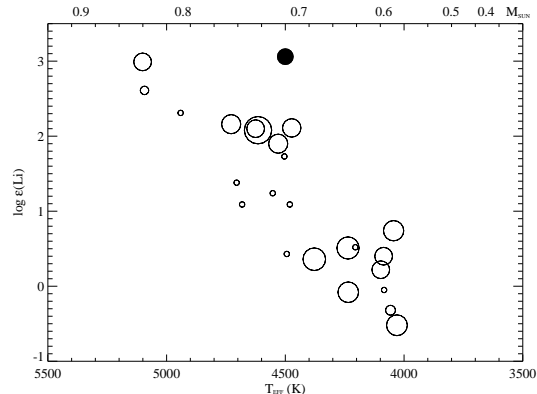


Fig. 7.— Li abundance of the secondary star in Cen X-4 (filled circle) in comparison with the abundances of different rotating Pleiades dwarf stars versus effective temperature from García López et al. (1994). The sizes of the circles are related to  $v \sin i$ . Stellar masses have been assigned following the evolutionary tracks of D’Antona & Mazzitelli (1994) for  $10^8$  yr.

(Martín et al. 1998; Stauffer et al. 1998). One could estimate an upper limit to the age of the system under the assumption that there is no mechanism able to enrich the atmosphere of the secondary star with freshly synthesized Li nuclei. In Fig. 8 we show the age of the system for different mass transfer rates and initial secondary masses by following the Li depletion in low mass stars according to evolutionary tracks of Siess et al. (2000). We have adopted the NLTE Li abundance and the present value for the initial metallicity of the system since a possible metallicity enrichment due to a SN explosion would have taken place early enough (at  $\sim 7$  Myr) and it would make the secondary follow the Li depletion as a metal-rich star. In any case, this metallicity effect is only relevant for masses higher than  $0.8 M_{\odot}$ . Such high Li abundance restricts the age of the system to the range  $\sim 10\text{--}70$  Myr. This age is quite short compared to the age assumed in the proposed evolutionary scenarios for the system, where an age of a few times  $10^9$  yr is required (e.g. Chevalier et al. 1989). These age constraints are obtained using models that do not consider the impact of high rotation on the Li depletion. According to Martín & Claret (1996) high rotation may inhibit the rate of Li depletion; therefore, the constraints

on age should be strictly considered as a lower limit. The effect of rotation on Li depletion has been measured in Pleiades stars with masses in the range  $0.6\text{--}0.8 M_{\odot}$  (see, for example, García López et al. 1994). The kinematic properties of Cen X-4 suggest that it could have been at the inner regions of the Galactic disk about 100–200 Myr ago (González Hernández et al. 2005). If the neutron star formed at that time as a result of an SN explosion, this might explain the high Li abundance of the system without postulating a Li production mechanism.

For such a young age the effect of the mass transfer in the secondary’s mass is negligible, and initial secondary masses higher than  $0.8 M_{\odot}$  can therefore be ruled out. Note that the mass transfer rate inferred from the observed quiescent X-ray luminosity ( $\sim 2.4 \times 10^{32} \text{ erg s}^{-1}$ , Asai et al. 1996) is very low  $\sim 10^{-6}$  the Eddington rate ( $\sim 3 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$ , Yi & Narayan 1997). On the other hand, Menou & McClintock (2001) have suggested a mass transfer rate of  $\sim 3 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$  based on optical–UV emission spectrum of the system.

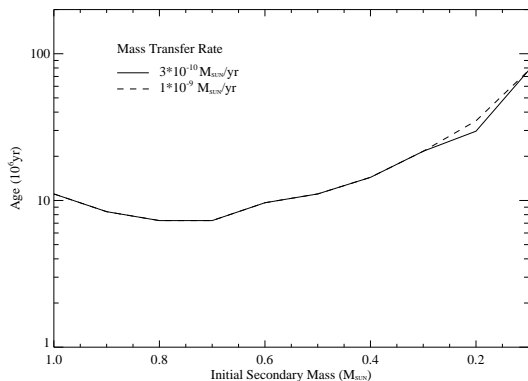


Fig. 8.— Upper limit to the age of the Cen X-4 system according to the Li abundance of the secondary star versus initial stellar masses of the secondary star, assuming different mass transfer rates. Li depletion has been followed according to the evolutionary tracks of Siess et al. (2000).

High Li abundances appear to be a common property of late-type companions in Soft X-ray Transients (SXTs), characterized by strong X-ray outbursts (usually lasting for several months) followed by long quiescent periods of  $\sim 10\text{--}50 \text{ yr}$ . Different models have been proposed to explain

these Li over-abundances in terms of spallation reactions or  $\alpha\text{--}\alpha$  reactions. Martín et al. (1994b) proposed that Li production could come from nuclear reactions in the accretion disk during outburst and being deposited on the companion via a disk wind. They argued that the observed abundance must correspond closely to the long term average since the depletion time scale ( $\tau_D \gtrsim 10^7 \text{ yr}$ ) is much longer than the recurrence time of outburst ( $\sim 30 \text{ yr}$ ). Later on, Yi & Narayan (1997) investigated the same scenario, in an advection-dominated accretion flow (ADAF), rather than a Shakura–Sunyaev disk not only during outburst but also in quiescence, although Li production during outburst may even dominate over the production in quiescence. This model can explain the observed Li abundance in Cen X-4 only if the mass-accretion rate in quiescence is  $\sim 10^{-3}$  times the Eddington rate and if there is a “propeller” effect. More recently, Guessoum & Kazanas (1999) have proposed Li production via neutron spallation of CNO elements in the secondary star. In this scenario, a flux of neutrons produced in the hot accretion flow around the compact object could escape easily and impinge on the secondary surface and then produce spallation of heavier elements. A short exposure to the above flux, i.e., during outbursts, would suffice to produce the observed enhancement.

A main sequence K star of mass  $\sim 0.1\text{--}0.8 M_{\odot}$  would destroy all its primordial Li abundance in  $\lesssim 80 \text{ Myr}$ . Yi & Narayan (1997, see also references therein) have discussed in some detail the question of Li depletion in the atmosphere of the companion star once it has been deposited/produced there, considering the possibility of a steady state, in which the enrichment and depletion rates should be equal, as suggested by Martín et al. (1994b). Martín et al. (1994a) remarked that isotopic ratios  ${}^7\text{Li}/{}^6\text{Li}$  as low as 5 are expected and hence would provide a proof of the spallation scenario. Unfortunately, at such high Li abundances there is degeneracy between Li abundance and isotopic ratio and consequently, different Li abundances and different isotopic ratios give rise to the same line strength. Higher S/N spectra are required to extract this information from the  $6708 \text{ \AA}$  Li line although the high rotational velocity of the star might make it very difficult. In addition, Guessoum & Kazanas (1999) suggested the possible en-

hancement of other light elements such as Be and B that might be analyzed using UV transitions.

## 5. Conclusions

We have obtained a high quality spectrum of the secondary star in Cen X-4 and derived atmospheric parameters and chemical abundances of several elements. We have applied a technique that provides a determination of the stellar parameters taking into account any possible veiling from the accretion disk. We find  $T_{\text{eff}} = 4500 \pm 100$  K,  $\log g = 3.9 \pm 0.3$ , and a disk veiling (defined as  $F_{\text{disk}}/F_{\text{total}}$ ) of less than 55 per cent at 5000 Å and decreasing towards longer wavelengths.

The abundances of Fe, Ca, Ti, Al, and Ni are super solar. The abundance ratios of each element with respect to Fe were compared with these ratios in late-type main sequence metal-rich stars. Moderate anomalies for Ni and Ti have been found. A comparison with element yields from spherically symmetric supernova explosion models suggests that the secondary star could have captured part of the ejecta from a supernova that also originated the compact object in Cen X-4 if the primordial abundances of the secondary star were solar. The observed abundances can be explained if a progenitor with a  $\sim 4 M_{\odot}$  helium core exploded with a mass cut  $\sim 1.5 M_{\odot}$ , such that a significant amount of iron could escape from the collapse of the inner layers, and hence the ejecta could also have enhanced the iron abundance in the secondary star.

The high galactic latitude of the system might suggest that the system could have originated in the Galactic halo and later enriched by nucleosynthetic products ejected in the supernova but our model computations for low metallicities show that this possibility is unlikely. In addition, the kinematic properties of this system (González Hernández et al. 2005) suggest that a natal kick was imparted to the neutron star at birth due to an asymmetric mass ejection and/or an asymmetry in the neutrino emission. We have also inspected a non-spherically symmetric SN explosion model but this model cannot produce acceptable fits to the observed abundances in the secondary star.

The Li abundance in the secondary star in Cen X-4 is dramatically high in comparison with field late-type main sequence stars, possibly indi-

cating that this is a young system ( $\sim 10\text{--}80$  Myr). Alternatively, if the system is much older a Li production mechanism is needed to balance the large destruction of Li expected in such low-mass stars.

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