CHEMICAL ABUNDANCES OF THE SECONDARY STAR IN THE BLACK HOLE X-RAY binary XTE J1118+480

Jonay I. González Hernández,1,2,3 Rafael Rebolo,3,4 Garik Israelian,3 Alexei V. Filippenko,5 Ryan Chornock,2 Nozomu Tominaga,6 Hideyuki Umeda,6 and Ken’ichi Nomoto6,7,8

Received 2007 November 24; accepted 2008 January 31

ABSTRACT

Following recent abundance measurements of Mg, Al, Ca, Fe, and Ni in the black hole X-ray binary XTE J1118+480 using medium-resolution Keck II ESI spectra of the secondary star, we perform a detailed abundance analysis including the abundances of Si and Ti. These element abundances, which are higher than solar, indicate that the black hole in this system formed in a supernova event, whose nucleosynthetic products could pollute the atmosphere of the secondary star, providing clues to the possible formation region of the system, either Galactic halo, thick disk, or thin disk. We explore a grid of explosion models with different He core masses, metallicities, and geometries. Metal-poor models associated with a formation scenario in the Galactic halo provide unacceptable fits to the observed abundances, allowing us to reject a halo origin for this X-ray binary. The thick-disk scenario produces better fits, although they require substantial fallback and very efficient mixing processes between the inner layers of the explosion and the ejecta, making an origin in the thick disk quite unlikely. The best agreement between model predictions and the observed abundances is obtained for metal-rich progenitor models. In particular, non-spherically symmetric models are able to explain, without strong assumptions of extensive fallback and mixing, the observed abundances. Moreover, asymmetric mass ejection in a supernova explosion could account for the required impulse necessary to launch the system from its formation region in the Galactic thin disk to its current halo orbit.

Subject headings: black hole physics — stars: abundances — stars: evolution — stars: individual (XTE J1118+480) — supernovae: general — X-rays: binaries

Online material: color figures

1. INTRODUCTION

The low-mass X-ray binary XTE J1118+480 is the first identified black hole moving in Galactic halo regions (Wagner et al. 2001; Mirabel et al. 2001). Since it was discovered during a faint outburst on UT 2000 March 29 (Remillard et al. 2000), it has been intensively studied in both the X-ray and optical spectral regions. During the decay of the outburst, McClintock et al. (2001) and Wagner et al. (2001) determined the radial velocity curve of the companion star, yielding a mass function $f(M) \approx 6 M_\odot$. The companion star was classified as a late-type main-sequence star with a mass of $0.1-0.5 M_\odot$ (Wagner et al. 2001).

By modeling the light curve, McClintock et al. (2001) derived a lower limit to the orbital inclination, $i \geq 55^\circ$, and consequently an upper limit to the black hole mass of $M_{\text{BH}} \leq 10 M_\odot$. Additional evidence for a high inclination ($i \approx 60^\circ$) comes from measurements of tidal distortion (Frontera et al. 2001), whereas the lack of dips or eclipses for a Roche lobe–filling secondary yields upper limits of $i \geq 80^\circ$ and $M_{\text{BH}} \geq 7.1 M_\odot$. Later, Gelino et al. (2006) derived an orbital inclination of $68^\circ \pm 2^\circ$ by modeling the optical and infrared ellipsoidal light curves of the system in quiescence. This value of the inclination allowed them to better constrain the black hole mass at $M_{\text{BH}} = 8.53 \pm 0.60 M_\odot$.

The system is located in the Galactic halo, with an extraordinarily high Galactic latitude ($b \approx 62.3^\circ$) and a height of $\sim 1.6$ kpc above the Galactic plane, according to its distance of $1.85 \pm 0.36$ kpc (Wagner et al. 2001). This appears surprising, since all other known black hole binaries are located in the Galactic disk. An accurate measurement of its proper motion, coupled with its distance, provided space-velocity components ($U$, $V$) that seem consistent with those of some old halo globular clusters (Mirabel et al. 2001). This opened the possibility that the system originated in the Galactic halo and, therefore, that the black hole could be either the remnant of a supernova (SN) in the very early Galaxy or the result of the direct collapse of an ancient massive star. However, the Galactocentric orbit crossed the Galactic plane many times in the past, and the system could have formed in the Galactic disk and been launched into its present orbit as a consequence of the “kick” imparted during the SN explosion of a massive star (Gualandris et al. 2005). Recent observations with the 10 m Keck II Telescope have revealed that the secondary star has a supersolar surface metallicity ($[\text{Fe}/\text{H}] = 0.2 \pm 0.2$; González Hernández et al. 2006), confirming the origin of the black hole in a SN event. Thus, if the system originated in the Galactic halo the element abundances of the secondary star must have been enriched by a factor of 5–25, depending on whether its initial metallicity resembled that of a thick-disk star or a halo star.
Element abundances of the secondary stars in X-ray binaries have been studied for the systems Nova Sco 1994 (Israelian et al. 1999; González Hernández et al. 2008), A0620−00 (González Hernández et al. 2004), Centaurus X-4 (González Hernández et al. 2005), XTE J1118+480 (González Hernández et al. 2006, hereafter Paper I), and V4641 Sagittarii (Orosz et al. 2001; Sadakane 2006). All of these X-ray binaries show metallicities close to solar, independent of their location with respect to the Galactic plane, and possible scenarios of pollution from a SN or hypernova have been discussed. In this paper, we compare in detail different scenarios for the possible enrichment of the secondary star from SN yields, providing conclusions about the formation region (Galactic halo, thick disk, or thin disk) of this halo black hole X-ray binary.

2. OBSERVATIONS

As already reported in Paper I, we obtained 74 medium-resolution spectra of the black hole X-ray binary XTE J1118+480 in quiescence with the Echelle Spectrograph and Imager (ESI; Sheinis et al. 2002) at the 10 m Keck II Telescope on UT 2004 February 14. The data cover the spectral range 4000−9000 Å at a resolving power \( \lambda / \Delta \lambda \approx 6000 \). We also observed 10 template stars with spectral types in the range K0 V to M2 V with the same instrument and spectral configuration. The exposure time was fixed at 300 s to minimize the effects of orbital smearing, which for the orbital parameters of XTE J1118+480 is in the range 0.6−26.6 km s\(^{-1} \), smaller than the instrumental resolution of 50 km s\(^{-1} \). All of the spectra were reduced in a standard manner.

3. REVISED ORBITAL PARAMETERS

We extracted the radial velocities by cross-correlating each target spectrum with the spectrum of a K5 V template star, rather than the later spectral types (K7/K8 V or even M) suggested by previous studies (Wagner et al. 2001; Torres et al. 2004).

We should remark that the spectrum of the secondary star in this system and the spectra of the template stars were normalized using the same procedure. The continuum was fitted with a low-order spline, in order to avoid the smoothing of possible existing broad TiO bands. Following Marsh et al. (1994), we computed the optimal value of \( v \sin i \) by subtracting broadened versions of the K5 V template (in steps of 1 km s\(^{-1} \)) and minimizing the residuals. We used a spherical rotational profile with linearized limb darkening \( c = 0.8 \) (Al-Naimiy 1978) due to the spectral type K of the secondary star. The best fit corresponds to \( v \sin i = 100 \pm 1 \) km s\(^{-1} \), where the uncertainties have been derived by assuming extreme cases for \( c = 0−1 \). Our derived rotational velocity, combined with our value of the velocity amplitude, \( K_2 \), implies a binary mass ratio \( q = 0.027 \pm 0.009 \), in agreement with previous results (Torres et al. 2004 and references therein).

4. CHEMICAL ANALYSIS

4.1. Stellar Parameters

The normalized spectra of X-ray transients, even when observed in quiescence, show apparently weaker stellar lines of the secondary star because of the veiling caused by the accretion disk. The veiling in XTE J1118+480 was estimated to be \( \sim 65\% \pm 8\% \) in the spectral range 5800−6400 Å in 2000 December and 2001 January and \( \sim 40\% \pm 10\% \) in 2003 January, by using standard optimal subtraction techniques with K5−M0 V template stars.

As described in Paper I, we tried to infer the stellar parameters, \( T_{\text{eff}} \) and \( \log g \), and the metallicity [Fe/H], of the secondary star taking into account the veiling from the accretion disk, defined as a linear function of wavelength and thus described with two additional parameters, the veiling at 4500 Å, \( f_{\text{disk}} \), and the slope, \( m_{\text{po}} \). Note that the total flux is defined as \( F_{\text{total}} = F_{\text{disk}} + F_{\text{sec}} \), where \( F_{\text{disk}} \) and \( F_{\text{sec}} \) are the flux contributions of the disk and the continuum of the secondary star, respectively. This procedure involves a \( \chi^2 \) minimization routine that compares several features of the stellar spectrum with a grid of synthetic spectra computed using the LTE code MOOG (Sneden 1973).

We used a grid of LTE model atmospheres (Kurucz 1993) and atomic line data from the Vienna Atomic Line Database (VALD;...
Piskunov et al. 1995). The oscillator strengths of relevant lines were adjusted until they reproduced the Kurucz et al. (1984) solar atlas with solar abundances (Grevesse et al. 1996). The changes we applied to the log \( g_f \)–values taken from the VALD were \( \Delta \log g_f \leq 0.2 \).

We selected nine spectral features containing in total 30 lines of Fe\textsc{i} and eight lines of Ca\textsc{i} with excitation potentials between 1 and 5 eV. The five free parameters were varied within the ranges given in Table 1. For each given iron abundance in the range \([\text{Fe/H}] < 0\), the Ca abundance was fixed according to the Galactic trend of Ca (Bensby et al. 2005), while for \([\text{Fe/H}] > 0\) we assumed \([\text{Ca/Fe}] = 0\). A rotational broadening of 100 km s\(^{-1}\) was adopted. The microturbulence, \( \xi \), was computed using an experimental expression as a function of effective temperature and surface gravity (Allende Prieto et al. 2004).

The result, already presented in Paper I, provides as most likely values \( T_{\text{eff}} = 4700 \pm 100 \) K, \( \log g (\text{cm s}^{-2}) = 4.6 \pm 0.3 \), \([\text{Fe/H}] = 0.18 \pm 0.17 \), \( f_{4500} = 0.85 \pm 0.20 \), and \( m_0 = -0.0002 \pm 0.0001 \). The 1 \( \sigma \) uncertainties of the five free parameters were determined using 1000 realizations, whose corresponding histograms are displayed in Figure 3.

The stellar parameters derived, especially the effective temperature, could have important implications for the Gelino et al. (2006) determination of the orbital inclination of the system \( (i \approx 68^\circ) \). These authors modeled the optical and infrared ellipsoidal light curves of XTE J1118+480 in quiescence, assuming a K7 V spectral type \( (T_{\text{eff}} \approx 4250 \) K\) for the secondary star. However, our spectroscopic value \( (T_{\text{eff}} \approx 4700 \) K\) would require more contribution of the flux from the accretion disk in the \( \text{K} \) band. Gelino et al. (2001) derived an inclination of \( i \approx 41^\circ \), yielding a black hole mass of \( M_{\text{BH}} \approx 11 M_\odot \) for the A0620–00 system, by adopting \( T_{\text{eff}} \approx 4600 \) K, which is 300 K lower than the spectroscopic value reported in González Hernández et al. (2004). Hynes et al. (2005) suggested that this different effective temperature of the secondary star in A0620–00 would require a larger disk contribution in the \( \text{K} \) band and, therefore, a higher inclination. In fact, Gelino et al. (2001) commented that if the \( \text{K} \)-band disk veiling were as high as 50% of the total flux, the derived inclination would increase to 60\(^\circ\). The black hole mass would then drop to \( M_{\text{BH}} \approx 5 M_\odot \). Although this is an extreme case, milder infrared veiling could still have a substantial impact on the derived black hole mass. Similarly, the black hole mass in XTE J1118+480 might be significantly affected if one uses our value of the effective temperature.

### 4.2. Stellar Abundances

We inspected several spectral regions in the observed Keck ESI spectrum of the secondary star, searching for suitable lines for a detailed chemical analysis. Using the derived stellar parameters, we first determined the Fe abundance by comparing synthetic spectra with each individual feature in the ESI spectrum (see Table 2). In Figures 4–6 here and Figure 1 of Paper I, we display some of the spectral regions analyzed to obtain the Fe abundance. These figures also show the best synthetic spectral fit to the observed spectrum of a template star (HIP 17420, with \( T_{\text{eff}} = 4801 \) K, \( \log g = 4.633 \), and \( [\text{Fe/H}] = -0.14 \)) using the

| TABLE 1 |
|------------------|--------|--------|
| Parameter        | Range  | Step   |
| \( T_{\text{eff}} \) (K) | 3500 – 5000 | 100    |
| \( \log g (\text{cm s}^{-2}) \) | 4 – 5 | 0.1    |
| \([\text{Fe/H}] \) | -1.5 – 1 | 0.1    |
| \( f_{4500} \) | 0 – 2 | 0.1    |
| \( m_0 \) | 0 – -0.00091 | -0.00010 |

Fig. 2.— Observed spectrum of the secondary star of XTE J1118+480 (top) and of two properly broadened templates (BD –05 3763, middle; BD +52 857, bottom).
stellar parameters and abundances determined by Allende Prieto et al. (2004). We only use as abundance indicators those features that were well reproduced in the template star. The chemical analysis is summarized in Table 2. The errors in the element abundances show their sensitivity to the uncertainties in the effective temperature ($\Delta_{T_e}$), gravity ($\Delta_{\log g}$), veiling ($\Delta_{\text{veil}}$), and the dispersion of the measurements from different spectral features ($\Delta_{\sigma}$). In Table 2 we also state the number of features analyzed for each element.

The abundances of Ti and Si were mainly derived from several lines in the spectral region 5920–5960 Å, where some telluric lines are present. However, since 74 spectra with different radial velocities in the range $\pm 710$ km s$^{-1}$ were combined to generate the average spectrum of the secondary star, these telluric lines must have been smoothed out.

The Mg abundance was derived from one spectral line (see Fig. 5) and the error associated with the dispersion of the measurements, $\sigma$, was assumed to be the average dispersion of Fe, Ca, and Ni abundances, and in this case $\Delta_{\sigma} = \sigma$. The same prescription was adopted for the analysis of Al and Li (see Fig. 1 of Paper I). The best fit to the Li $i$ 6708 Å feature provides an LTE abundance of $\log (\text{Li})_{\text{LTE}} = 1.61 \pm 0.25$. We estimated the non-LTE abundance correction$^9$ for this element from the theoretical LTE and non-LTE curves of growth in Pavlenko & Magazzù (1996). We found $\Delta_{\text{NLTE}} = 0.17$. Because of the weakness of the absorption, we consider this abundance estimate given in Table 2 to be an upper limit.

5. DISCUSSION

As discussed in Paper I, the Fe abundance of the secondary star is slightly higher than solar but similar to that of many

![](image)

Fig. 3.— 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.

$^9 \Delta_{\text{NLTE}} = \log \epsilon (X)_{\text{NLTE}} - \log \epsilon (X)_{\text{LTE}}$. 
TABLE 2

| Element | [X/H]_{LTE} | \Delta_\sigma | \Delta_{\sigma_{\text{fe}}} | \Delta_{\log g} | \Delta_{\text{veil}} | \Delta_{\text{tot}}^b | \eta_{\text{num}} | \eta_{\text{tot}}^c |
|---------|-------------|---------------|------------------|--------------|----------------|----------------|---------|---------|
| Mg...... | 0.35        | 0.12          | 0.00             | -0.10        | 0.20           | 0.25           | 1       |         |
| Al...... | 0.60        | 0.12          | 0.00             | 0.15         | 0.20           | 0.20           | 1       |         |
| Si...... | 0.37        | 0.03          | -0.07            | 0.07         | 0.18           | 0.21           | 2       |         |
| Ca...... | 0.15        | 0.03          | 0.13             | -0.16        | 0.11           | 0.23           | 5       |         |
| Ti...... | 0.32        | 0.18          | 0.12             | -0.03        | 0.14           | 0.26           | 3       |         |
| Fe...... | 0.18        | 0.08          | 0.06             | 0.04         | 0.13           | 0.17           | 5       |         |
| Ni...... | 0.30        | 0.10          | 0.12             | 0.14         | 0.14           | 0.21           | 2       |         |
| Li^a..... | 1.78        | 0.12          | 0.15             | 0.05         | 0.15           | 0.25           | 1       |         |

Note.—The uncertainties from the dispersion of the best fits to different features, \(\Delta_\sigma\), are estimated using the formula \(\Delta_\sigma = \sigma / \sqrt{N}\), where \(\sigma\) is the standard deviation of the measurements.

a Element abundances of the secondary star (calculated assuming LTE) are \([X/H] = \log [(X) / (H) \text{N(LTE)}] - \log [(X) / (H)]_\odot\), where \((X)\) is the number density of atoms. Uncertainties, \(\Delta(X) / \text{H}\), are at the 1\(\sigma\) level and take into account the uncertainties in the stellar and veiling parameters.

b The total error is estimated as \(\Delta_{\text{tot}} = \sqrt{\Delta_{\sigma_{\text{fe}}}^2 + \Delta_{\log g}^2 + \Delta_{\text{veil}}^2 + \Delta_{\text{ext}}^2}\).

c Number of features analyzed for each element.

d Li abundance is expressed as \(\log (\text{Li}) / (\text{H}) \text{NLTE} + 12\).

stars in the solar neighborhood. The abundances of other elements listed in Table 2 relative to iron are compared in Figure 7 with the Galactic trends of these elements in the relevant range of metallicities. Moderate anomalies are found only for Al. In Table 3, we show the element abundance ratios in the secondary star in XTE J1118+480 and the average values in stars with iron content in the range \(0.01 < [\text{Fe/H}] < 0.35\), the comparison sample, corresponding to a 1\(\sigma\) uncertainty in the iron abundance of the companion star. Whereas Ca and Ti are consistent with the average values of the comparison sample, Ni and Si, at 1\(\sigma\), and especially Al, at 2\(\sigma\), appear to be more abundant than the average values of the stars in the comparison sample.

The present location and space-velocity components \((U, V)\) of the system might suggest that it belongs to the Galactic halo, but the derived metallicity makes this possibility less likely. One could include the metallicity in the expression given by Bensby et al. (2005; their eq. [A.1]) to estimate the relative likelihoods that a star belongs to the Galactic thin disk, thick disk, or halo. The equations can be written as follows:

\[
P_{\text{thin disk}} = f_D P_D, \quad P_{\text{thick disk}} = f_{TD} P_{TD}, \quad P_{\text{halo}} = f_H P_H
\]

where the subscript \(i\) indicates one of the three populations “D” (thin disk), “TD” (thick disk), and “H” (halo). The total probability \(P\) takes into account the fraction of stars belonging to each population in the solar neighborhood (\(f_D = 0.94, f_{TD} = 0.06, \text{and } f_H = 0.0015\); Bensby et al. 2003). The velocity distributions of...
were taken from Gilli et al. (2006). The size of the cross indicates the uncertainty. Filled and empty circles correspond to abundances for exoplanet host stars and stars without known exoplanet companions, respectively. The dash-dotted lines indicate solar abundance values.

For the element abundance ratios in the secondary star in XTE J1118+480, taken from Gilli et al. (2006), the uncertainty in the average value of abundance ratios in the comparison sample is obtained as \( \Delta_{\text{avg}} = \sigma_{\text{avg}} / \sqrt{N} \), where \( \sigma_{\text{avg}} \) is the standard deviation of the measurements and \( N \) is the number of stars.

Table 3: Element Abundance Ratios in XTE J1118+480

| Element | \([X/Fe]_{\text{XTE 1118}}\) | \(\Delta_{[X/Fe]}_{\text{XTE 1118}}\)^a | \([X/Fe]_{\text{stars}}\) | \(\sigma_{\text{stars}}\) | \(\Delta_{\text{stars}}\) |
|---------|----------------|----------------|----------------|----------------|----------------|
| Mg      | 0.17           | 0.22           | 0.02           | 0.08           | 0.02           |
| Al      | 0.42           | 0.15           | 0.14           | 0.10           | 0.02           |
| Si      | 0.19           | 0.17           | -0.03          | 0.04           | 0.01           |
| Ca      | -0.03          | 0.23           | -0.13          | 0.05           | 0.01           |
| Ti      | 0.14           | 0.22           | 0.05           | 0.08           | 0.01           |
| Ni      | 0.12           | 0.12           | -0.02          | 0.05           | 0.01           |

Note.—The \([X/Fe]_{\text{stars}}\) indicate the average values of 24 stars with iron content in the range 0.01–0.35, corresponding to 1σ in the \([Fe/H]\) abundance of the secondary star in XTE J1118+480, taken from Gilli et al. (2006). The uncertainty in the average value of abundance ratios in the comparison sample is obtained as \( \Delta_{[X/Fe]} = \sigma_{[X/Fe]} / \sqrt{N} \), where \( \sigma_{[X/Fe]} \) is the standard deviation of the measurements and \( N \) is the number of stars.

^a Uncertainties in the element abundance ratios ([X/Fe]) in the secondary star in XTE J1118+480.

Fig. 7.—Abundance ratios of the secondary star in XTE J1118+480 (large crosses) compared with the abundances of G and K metal-rich dwarf stars. Galactic trends were taken from Gilli et al. (2006). The size of the cross indicates the uncertainty. Filled and empty circles correspond to abundances for exoplanet host stars and stars without known exoplanet companions, respectively. The dash-dotted lines indicate solar abundance values.

In the comparison sample, the uncertainty in the range 0.01–0.35, corresponding to 1σ in the ([Fe/H]) abundance of the secondary star in XTE J1118+480, taken from Gilli et al. (2006). The uncertainty in the average value of abundance ratios in the comparison sample is obtained as \( \Delta_{[X/Fe]} = \sigma_{[X/Fe]} / \sqrt{N} \), where \( \sigma_{[X/Fe]} \) is the standard deviation of the measurements and \( N \) is the number of stars.

The system could also have originated as a consequence of an encounter of an ancient black hole of the Galactic halo with a single star or a binary of two solar-type stars in the Galactic disk. However, this possibility is very unlikely because of the extremely low density of stars in the disk (~0.006 pc–3; Mihalas & Binney 1981). The orbit of the system, integrated backward in time, never crosses the Galactic plane through the inner 2 kpc (Gualandris et al. 2005), so high-density regions near the Galactic center are discarded. Portegies Zwart et al. (1997a) have modeled the encounter of black holes in high-density systems. In such systems, where the density of stars is \( \sim 4 \times 10^{6} \) pc–3 (10^9 times higher than in the Galactic disk), a black hole spends 1.5 Gyr before it suffers a tidal capture by a main-sequence star. In addition, the cases in which a black hole can capture an isolated star or one star of a binary require very stringent constraints on the closest approach and impact velocity (Benz & Hills 1992; Hills 1991). All of these factors make this possibility very unlikely.

Therefore, in conclusion, the present location, velocity, and metallicity of the secondary star in XTE J1118+480 suggest that the black hole formed in a supernova or hypernova explosion that occurred within the binary system. This explosive event must have either provided a kick to the system, if it was formed in the...
thin disk, or enriched significantly the atmosphere of the secondary star, if the system formed in the thick disk or halo.

The present orbital separation between the compact object and the secondary star has been estimated to be $a_c \approx 2.67 R_\odot$ (Gelino et al. 2006). Thus, the secondary star could have captured a significant amount of the ejected matter in the SN explosion that formed the compact object. The chemical composition of the secondary star may provide information on the chemical composition of the progenitor of the compact object and, therefore, on the formation region (thin disk, thick disk, or halo) of the binary system. We next discuss the possibility that the SN explosion of the massive progenitor enriched the secondary star from different initial metallicities.

5.1. Spherical Explosion

Gelino et al. (2006) derived a current black hole mass of $M_{BH,f} = 8.53 \pm 0.60 M_\odot$ and a secondary mass of $M_{2,f} = 0.37 \pm 0.03 M_\odot$. Using near-UV spectroscopic observations of the accretion disk, Haswell et al. (2002) suggested that the material accreted onto the compact object is substantially CNO-processed, indicating that the initial mass of the secondary star could have been as high as $\approx 1.5 M_\odot$. Hereafter we adopt an initial secondary mass of $M_{2,i} = 1.0 M_\odot$ and a black hole mass of $M_{BH,i} = 8.0 M_\odot$.

A binary system such as XTE J1118+480 will survive a spherical SN explosion if the ejected mass $\Delta M = M_{He} - M_{BH,i} \leq (M_{He} + M_{2,i})/2$ (Hills 1983). This implies a mass for the He core before the SN explosion of $M_{He} \leq 17 M_\odot$. Using the expressions given by Portegies Zwart et al. (1997b and references therein), we infer a He core radius of $R_{He} \approx 2-3 R_\odot$ for He core masses in the range $M_{He} \approx 8.5-17 M_\odot$. We will assume that the post-SN orbital separation after tidal circularization of the orbit is in the range $a_{c,f} \approx 4-6 R_\odot$, since the secondary star has experienced significant mass and angular momentum losses during the binary evolution until reaching its present configuration, with $a_{c,f} \approx 2.67 R_\odot$.

Assuming a pre-SN circular orbit and an instantaneous, spherically symmetric ejection (i.e., shorter than the orbital period), one can estimate the pre-SN orbital separation, $a_0$, using the relation given by van den Heuvel & Habets (1984): $a_0 = a_{c,f} R_\odot$, where $a_{c,f} = (M_{BH,i} + M_{2,i})/(M_{He} + M_{2,i})$. We find $a_0 \approx 3-5$, essentially depending on the adopted values of $M_{He}$ and $a_{c,f}$. At the time of the SN explosion ($\approx 5-6$ Myr; Brunnish & Truran 1982), a $1 M_\odot$ secondary star, still in its pre–main-sequence evolution, has a radius $R_{2,i} \approx 1.3 R_\odot$ and a convective zone of mass $M_{cz} \approx 0.652 M_\odot$ (D’Antona & Mazzitelli 1999). Thus, the amount of mass deposited on the secondary can be estimated as $m_{cap} = \Delta M (\pi R_{2,i}^2/4\pi a_0^2) f_{cap} M_\odot$, where $f_{cap}$ is the fraction of mass, ejected within the solid angle subtended by the secondary star, that is eventually captured. We assume that the captured mass $m_{cap}$ is efficiently mixed with the mass of the convective zone, $M_{cz}$.

We compute the expected abundances in the atmosphere of the secondary star after the pollution from the progenitor of the compact object as in González Hernández et al. (2004). We used $40 M_\odot$, spherically symmetric core-collapse explosion models ($M_{He} \approx 15.1-16.1 M_\odot$) for different metallicities ($Z = 0, 0.001, 0.004, 0.02$) and explosion energies (Umeda & Nomoto 2002, 2005; Tomimaga et al. 2007). These models imply $\Delta M \approx 7-8 M_\odot$ and require small capture efficiencies of $f_{cap} \approx 0.1$ (i.e., 10%) to significantly increase the metal content of the secondary star. On the other hand, the use of $30 M_\odot$ models ($M_{He} \approx 8.5-11.2 M_\odot$) would require $f_{cap} \approx 0.9-1$. These models would also provide a different mass fraction of each element at each value of the mass.
cut (the mass that initially collapses, forming the compact remnant). For more details of the models, see Tominaga et al. (2007).

The explosion energy, \( E_k = 1 \times 10^{51} \) ergs and \( E_k = (20–30) \times 10^{51} \) ergs for the supernova and hypernova (HN) models (respectively), is deposited instantaneously 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 hydrodynamic code (Umeda & Nomoto 2002 and references therein). In our simple model, we have assumed different mass cuts and fallback masses and a mixing factor of 1, which assumes that all fallback matter is well mixed with the ejecta. The amount of fallback, \( M_{\text{fall}} \), is the difference between the final remnant mass, \( M_{\text{BH},i} \), and the initial remnant mass of the explosion, \( M_{\text{cut}} \). Recall here that the ejected mass \( \Delta M \) is equal to \( M_{\text{He}} - M_{\text{BH},f} \), where \( M_{\text{He}} \) is the mass of the He core.

We use the SN and HN models to provide us with the yields of the explosion before radiative decay of element species. We then compute the integrated, decayed yields of the ejecta by adopting a mass cut and by mixing all of the material above the mass cut. Finally, we calculate the composition of the matter captured by the secondary star, and we mix it with the material of its convective envelope.

In Figure 8, we show the expected abundances of the secondary star after contamination from the nucleosynthetic products of the SN explosion (\( E_k = 1 \times 10^{51} \) ergs) of \( M_{\text{BH},i} \approx 15–16 M_\odot \) progenitor stars. The initial abundances of the secondary star have been estimated from the average abundances of halo stars with metallicities of \( [\text{Fe/H}] \approx -2.2 \) (from Cayrel et al. 2004) and \( [\text{Fe/H}] \approx -1.4 \) (from Jonsell et al. 2005), thick-disk stars with \( [\text{Fe/H}] \approx -0.7 \) (from Jonsell et al. 2005), and thin-disk stars with \( [\text{Fe/H}] \approx 0 \) and \( [\text{Fe/H}] \approx 0.18 \) (from Gilli et al. 2006). For each simulation at each metallicity, we have fixed the factor \( f_{\text{cap}} \) at a value that allows us to approximately match the observed aluminum abundance.

We should remark that for a given model at a given metallicity, once the capture efficiency is fixed, the aluminum abundance in the secondary star hardly depends on the mass cut. For other figures in this paper, \( f_{\text{cap}} \) was changed until an abundance of \( [\text{Al/H}] \approx 0.5 \) was obtained, compatible with the observed abundance within the uncertainties.

From Figure 8 one can see that while Mg and Al remain significantly enhanced (above solar abundances) for all mass cuts at all metallicities, Si, Ca, Ti, Fe, and Ni are quite sensitive to the mass cut of the model. Thus, for metallicities below \( -1.4 \) dex, only \( M_{\text{cut}} \geq 3 M_\odot \) is able to enhance sufficiently the Ti, Fe, and Ni, whereas Ca and Si remain quite overabundant for \( M_{\text{cut}} \leq 4 M_\odot \) and \( M_{\text{cut}} \leq 5 M_\odot \) (respectively) at all metallicities. We should note that for metallicities \( [\text{Fe/H}] \leq -1.4 \) (i.e., \( Z \leq 0.001 \)), the expected abundances in the secondary star do not depend on the initial abundances, but on the SN yields. Thus, we found different expected abundances of the secondary between \( [\text{Fe/H}] \approx -1.4 \) and \( [\text{Fe/H}] \approx -2.2 \) because we used the SN \( Z = 0.001 \) model and the SN \( Z = 0 \) model, respectively.

5.2. Formation in the Halo

The kinematics of the system, at least \( U \) and \( V \), resemble those of halo stars, and therefore a significant kick during the black hole formation process appears unnecessary. Thus, a spherically symmetric SN explosion would provide the desired kick velocity to match the current velocity components of the system from initial velocities similar to those of halo stars. However, because of the extremely low metallicities of halo stars, it is required for the secondary to have captured enough matter from the ejecta to reach the current abundances.

In Figure 9, we compare the observed abundances with the expected abundances in the secondary star after having captured 17.5% of the matter ejected within the solid angle subtended by the secondary from a metal-poor \( (Z = 0.001) \) 40 \( M_\odot \) spherically symmetric supernova explosion \( (M_{\text{BH},i} = 15.8 M_\odot) \) with \( E_k = 10^{51} \) ergs for two different mass cuts, \( M_{\text{cut}} = 2.51 M_\odot \) (solid line with open circles) and \( M_{\text{cut}} = 3.01 M_\odot \) (dash-dotted line with open circles). The initial abundances of the secondary star were adopted for the average abundances of halo stars with \( [\text{Fe/H}] = -1.4 \pm 0.2 \), and the initial orbital distance was \( a_0 \approx 6 R_\odot \). (b) Same as (a), but for a spherically symmetric hypernova explosion \( (E_k = 30 \times 10^{51} \) ergs) for mass cuts of \( M_{\text{cut}} = 4.05 M_\odot \) (solid line with open circles) and \( M_{\text{cut}} = 5.03 M_\odot \) (dash-dotted line with open circles). [See the electronic edition of the Journal for a color version of this figure.]
was roughly reproduced, providing $f_{\text{cap}} \approx 0.17$. The parameters of the explosion models used in Figures 9–13 are given in Table 4. In Table 5, we show the expected abundances of the secondary star after contamination from metal-poor SN/HN explosion models.

With a supernova model, as shown in Figure 9a, it is not possible to recover the observed abundances, because these models produce too much Mg and Ca regardless of the Fe abundance obtained; in addition, the Ni abundance is strongly dependent on the mass cut. The hypernova model, displayed in Figure 9b, makes it even more difficult to fit the observed abundances, since this model creates too much Ca relative to Fe and Ni. As inferred from Figure 8, a model with initial abundances at [Fe/H] $\approx -2.2$ (Cayrel et al. 2004) would also not be successful in reproducing the observed abundances, because of the tremendous and different sensitivity of each element to the mass cut.

In conclusion, neither of these very metal-poor models is able to reproduce the observed abundances. We also tried to fit the observed abundances using a metal-poor 30 $M_\odot$ explosion model, but the agreement is even worse than for the 40 $M_\odot$ models, again because of the strong sensitivity of the element abundance to the mass cut. The comparison of the observed abundances with SN yields allows us to rule out a Galactic halo origin for this black hole binary.

5.3. Formation in the Thick Disk

The space-velocity components of the system are comparable to those of thick-disk stars, and its present location 1.6 kpc above the Galactic plane is slightly higher than the scale height of thick-disk stars ($\sim 0.8–1.3$ kpc; Reylé & Robin 2001; Chen 1997); thus, a strong kick during the SN explosion would not be required. The spherically symmetric SN explosion of 15.8 and 11 $M_\odot$ He cores provides impulses of $\sim 60$ and $\sim 20$ km s$^{-1}$, respectively. However, an enrichment from the typical abundances of thick-disk stars would have been necessary. In the simulations, the initial abundances were assumed to be the average values of thick-disk stars with [Fe/H] $\approx -0.7$ from Jonsell et al. (2005).

In Figure 10, we compare the expected abundances from a 40 $M_\odot$ explosion model for two energies and mass cuts (see also Table 5). Figure 10a shows the expected abundances from a SN model, which seems to better approach the observed abundances than those of halo-like metallicities. As in the previous figure, the $f_{\text{cap}}$ factor was changed until an abundance of [Al/H] $\approx 0.5$ was obtained, compatible with the observed abundance within the uncertainties. For the mass cut at 2.50 $M_\odot$, the model roughly fits the observed abundances except for Ca, which appears enhanced in the model by a factor of 2.6. Better agreement with Ca could be obtained if $f_{\text{cap}}$ were lowered, but then Al, Ni, and Ti would not match their observed abundances. If we increased the mass cut to 3.03 $M_\odot$, the Ca abundance only decreases by 0.15 dex, whereas Ti, Fe, and Ni decrease by factors of 2.6, and 4 (respectively), which makes the model unable to fit the observed abundances. The hypernova case offers worse results, since Si and Ca are no longer reproduced and Fe and Ni cannot be fitted at the same time.

For this metallicity we have also explored a 30 $M_\odot$ explosion model. The results are displayed in Figure 11. In Figure 11a the SN model is compared with the observations. For the lower mass cut, at 2.52 $M_\odot$, the model provides too-high Si and Ca abundances and too-low Ni abundance, whereas for a mass cut of 3.04 $M_\odot$ the observed Ti, Fe, and Ni abundances are too high compared with the model predictions. In the hypernova case (Fig. 11b), at these low mass cuts the model produces too much Si and Ca; in addition, Ti, Fe, and Ni are too sensitive to the location of the mass cut.

Despite the fact that none of the explosion models explored is able to fairly reproduce the observed abundances in the secondary
star, all of the models require vigorous mixing between the fallback matter and the final ejected matter (Kifonidis et al. 2000). For instance, in the 15.8 $M_\odot$ He core model, all of the material above the mass cut placed at 2.50 $M_\odot$ should be well mixed in order to convey heavy elements such as Fe and Ni to the outer layers of the explosion, which might make more unlikely a Galactic thick disk origin for XTE J1118+480.

### 5.4. Formation in the Thin Disk

In this scenario, the system must have acquired an impulse during the formation of the black hole that pushed it up from a Galactic plane orbit to the current halo orbit. The system should have been accelerated to a peculiar space velocity of $\sim$180 km s$^{-1}$ (Gualandris et al. 2005) to reach its present location, requiring an asymmetric kick. It has been suggested that such kicks can be imparted during the birth of nascent neutron stars, as a result of asymmetric mass ejection or an asymmetry in the neutrino emission (Lai et al. 2001 and references therein).

Podsiadlowski et al. (2002) proposed that the black hole in Nova Sco 1994 could have formed in a two-stage process whereby the initial collapse led to the formation of a neutron star accompanied by a substantial kick and the final mass of the compact remnant was achieved by matter that fell back after the initial collapse. However, the black hole mass in Nova Sco 1994 is estimated to be $\sim$5.4 $M_\odot$ (Beer & Podsiadlowski 2002), while the black hole in XTE J1118+480 has a mass of $\sim$8 $M_\odot$, which would require a fallback mass of $\sim$6.6 $M_\odot$ if we assume $\sim$1.4 $M_\odot$ for a canonical neutron star. This scenario might take place in the context of collapsar models, where the black hole would be formed in a mild explosion with substantial fallback (up to $\sim$5 $M_\odot$ is expected), as proposed by MacFadyen et al. (2001). Asymmetric mass ejection would relax this requirement, providing enough

---

**TABLE 5**

**Metal-poor Supernova/Hypernova Explosion Models in XTE J1118+480**

| Element | [X/H]$_{\text{Expected}}^a$ | [X/H]$_{\text{Expected}}^b$ | $M_{\text{cut,low}}^d$ | $M_{\text{cut,up}}^d$ | $M_{\text{cut,low}}^d$ | $M_{\text{cut,up}}^d$ |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 40 $M_\odot$ Explosion Model with $Z = 0.001$ | | | | | | |
| Mg | 0.35 | -1.08 | 0.83 | 0.85 | 0.75 | 0.79 |
| Al | 0.60 | -1.27 | 0.52 | 0.53 | 0.39 | 0.42 |
| Si | 0.37 | -1.13 | 0.88 | 0.89 | 1.08 | 1.09 |
| Ca | 0.15 | -1.12 | 0.74 | 0.75 | 1.09 | 1.01 |
| Ti | 0.32 | -1.15 | 0.14 | 0.11 | 0.54 | 0.12 |
| Fe | 0.18 | -1.46 | 0.47 | 0.14 | 0.63 | -0.22 |
| Ni | 0.30 | -1.48 | 1.09 | -0.52 | 0.14 | -0.81 |
| O | ... | -0.76 | 0.75 | 0.77 | 0.69 | 0.73 |
| C | ... | -0.86 | -0.54 | -0.53 | -0.60 | -0.58 |

| 40 $M_\odot$ Explosion Model with $Z = 0.004$ | | | | | | |
| Mg | 0.35 | -0.41 | 0.58 | 0.59 | 0.61 | 0.64 |
| Al | 0.60 | -0.46 | 0.51 | 0.52 | 0.41 | 0.44 |
| Si | 0.37 | -0.50 | 0.62 | 0.60 | 0.90 | 0.93 |
| Ca | 0.15 | -0.54 | 0.57 | 0.42 | 0.86 | 0.87 |
| Ti | 0.32 | -0.50 | 0.16 | -0.18 | 0.56 | 0.27 |
| Fe | 0.18 | -0.75 | 0.26 | -0.52 | 0.67 | 0.07 |
| Ni | 0.30 | -0.73 | 0.08 | -0.53 | 0.43 | -0.38 |
| O | ... | -0.26 | 0.71 | 0.73 | 0.67 | 0.69 |
| C | ... | -0.35 | 0.10 | 0.11 | 0.06 | 0.08 |

| 30 $M_\odot$ Explosion Model with $Z = 0.004$ | | | | | | |
| Mg | 0.35 | -0.41 | 0.60 | 0.62 | 0.57 | 0.62 |
| Al | 0.60 | -0.46 | 0.52 | 0.54 | 0.40 | 0.45 |
| Si | 0.37 | -0.50 | 0.77 | 0.54 | 1.02 | 0.95 |
| Ca | 0.15 | -0.54 | 0.72 | 0.17 | 1.03 | 0.82 |
| Ti | 0.32 | -0.50 | 0.18 | -0.41 | 0.66 | 0.01 |
| Fe | 0.18 | -0.75 | 0.14 | -0.71 | 0.71 | -0.32 |
| Ni | 0.30 | -0.73 | -0.43 | -0.54 | 0.40 | -0.40 |
| O | ... | -0.26 | 0.75 | 0.78 | 0.69 | 0.74 |
| C | ... | -0.35 | 0.02 | 0.03 | -0.04 | -0.01 |

**Note:** Expected abundances in the secondary atmosphere contaminated with nucleosynthetic products of metal-poor explosion models for two different explosion energies and mass cuts, presented in Figs. 9–11.

$^a$ Expected abundances of the secondary star.

$^b$ Observed abundances of the secondary star in XTE J1118+480.

$^c$ Initial abundances assumed for the secondary star in XTE J1118+480 (see text). The initial C and O abundances of the thick-disk model ([X/H]$_0 = 0.7$) were adopted from Ecuvillon et al. (2004, 2006).

$^d$ $M_{\text{cut,low}}$ and $M_{\text{cut,up}}$ are the lower and upper mass cuts adopted in the model computations. See the exact values in the legends of Figs. 9–11.
impulse to the system to be launched into its present orbit from the Galactic plane.

In Figure 12, we compare the expected abundances from the explosion of a 15.1 $M_\odot$ He core with the observed abundances of the secondary star (see also Table 6). As in the previous figures, the $f_{\text{cap}}$ factor was changed until an abundance of $[\text{Al/H}]=0.5$ was obtained, compatible with the observed abundance within the uncertainties. The initial abundances were assumed to match the average values of disk stars with similar iron content, which are provided in Table 3. For both the SN model (Fig. 12a) and the HN model (Fig. 12b), the observed element abundances can be reproduced for all mass cuts. This means that neither substantial fallback nor an efficient mixing process is needed. For mass cuts above $\sim 3 M_\odot$, very little Si, Ca, Ti, Fe, or Ni is ejected; thus, the expected abundances of the model essentially reflect the initial abundances of the secondary star. In contrast, Mg and Al are not sensitive to the mass cut and are slightly enhanced as a result of the capture of enriched material in the SN explosion.

We also investigated a model with solar initial abundances for the secondary star, that is, $[\text{X/H}]_{0}=0$, and the same explosion model of solar metallicity ($Z=0.02$), which can fit all of the element abundances if the mass cut is low enough ($M_{\text{cut}} \leq 3 M_\odot$) and mixing is so efficient that significant amounts of elements that form in the inner layers of the explosion (such as Ti, Ni, and Fe) are present in the ejecta.

5.5. Nonspherical Explosion: Formation in the Thin Disk

In this section, the thin-disk scenario is studied using nonspherically symmetric explosion models from Maeda et al. (2002). The chemical composition of the ejecta in a non–spherically symmetric supernova explosion models from Maeda et al. (2002).
symmetric SN explosion is strongly dependent on direction. In particular, if we assume that the jet is collimated perpendicular to the orbital plane of the binary, where the secondary star is located, elements such as Ti, Fe, and Ni are mainly ejected in the jet direction, while O, Mg, Al, Si, and S are preferentially ejected near the equatorial plane of the helium star (Maeda et al. 2002).

In Figure 13, we compare the predicted abundances in the secondary star after pollution from a model aspherical explosion of a metal-rich progenitor having a 16\( M_\odot \) He core (see also Table 6). The initial abundances of the secondary were extracted from the average values of stars of the solar neighborhood with similar iron content (see Table 3). Figure 13a reflects the composition of the material ejected in the equatorial plane, while in Figure 13b we have considered complete lateral mixing (Podsiadlowski et al. 2002)—that is, the ejected matter is completely mixed within each velocity bin. This mixing process is carried out with the decayed yields of the model, and after that all of the material above the mass cut is mixed and used to calculate the composition of the ejected matter. The observed abundances are better reproduced if complete lateral mixing is considered, since this process tends to enhance all of the element abundances at all mass cuts. However, the equatorial model (Fig. 13a) also provides good fits to the observed abundances. It should be noted that in this model, only the material ejected in the equatorial plane is captured, and therefore, only Mg, Al, and Si are significantly enhanced with respect to the initial abundances. A model with solar initial abundances for the secondary star, that is, [\( X/H \)]\(_0\) = 0, and the same explosion model of solar metallicity (\( Z = 0.02 \)) was also inspected, providing the same result except for Ti, Fe, and Ni in comparison with the observations.

Table 6 presents the expected abundances for two different mass cuts and symmetries, presented in Figs. 12 and 13.

\[
\begin{array}{llllllllll}
\text{Element} & \text{[X/H]} & \text{[X/H]}_0 & M_{\text{cut,low}} \times 10^{-3} & M_{\text{cut,up}} \times 10^{-3} & M_{\text{cut,low}} \times 10^{-3} & M_{\text{cut,up}} \times 10^{-3} \\
\text{Mg} & 0.35 & 0.17 & 0.32 & 0.30 & 0.32 & 0.30 \\
\text{Al} & 0.60 & 0.29 & 0.50 & 0.50 & 0.48 & 0.50 \\
\text{Si} & 0.37 & 0.12 & 0.22 & 0.14 & 0.28 & 0.14 \\
\text{Ca} & 0.15 & 0.02 & 0.09 & 0.02 & 0.15 & 0.02 \\
\text{Ti} & 0.32 & 0.20 & 0.24 & 0.21 & 0.34 & 0.21 \\
\text{Fe} & 0.18 & 0.18 & 0.30 & 0.18 & 0.32 & 0.18 \\
\text{Ni} & 0.30 & 0.13 & 0.35 & 0.15 & 0.32 & 0.15 \\
\text{O} & 0.18 & 0.18 & 0.33 & 0.33 & 0.33 & 0.33 \\
\text{C} & 0.11 & 0.16 & 0.15 & 0.16 & 0.15 & 0.16 \\
\end{array}
\]

The initial C and O abundances of the metal-rich models were adopted from Ecuvillon et al. (2004, 2006). The initial and O abundances of the metal-rich models were adopted from Ecuvillon et al. (2004, 2006). The initial abundances assumed for the secondary star in XTE J1118+480 are angular range, measured from the equatorial plane, in which all of the ejected material in the explosion has been completely mixed for each velocity point.

**Table 6** Metal-rich Supernova/Hypernova Explosion Models in XTE J1118+480

A. Spherical Explosion Model with \( Z = 0.02 \)

| Element | [X/H] \text{Expected} | [X/H]_0 | M_{\text{cut,low}} | M_{\text{cut,up}} |
|---------|----------------------|--------|-------------------|-------------------|
| Mg      | 0.35                 | 0.17   | 0.32              | 0.30              |
| Al      | 0.60                 | 0.29   | 0.50              | 0.50              |
| Si      | 0.37                 | 0.12   | 0.22              | 0.14              |
| Ca      | 0.15                 | 0.02   | 0.09              | 0.02              |
| Ti      | 0.32                 | 0.20   | 0.24              | 0.21              |
| Fe      | 0.18                 | 0.18   | 0.30              | 0.18              |
| Ni      | 0.30                 | 0.13   | 0.35              | 0.15              |
| O       | 0.18                 | 0.18   | 0.33              | 0.33              |
| C       | 0.11                 | 0.16   | 0.15              | 0.16              |

B. Aspherical Explosion Model with \( Z = 0.02 \)

| Element | [X/H] \text{Expected} | [X/H]_0 | M_{\text{cut,low}} | M_{\text{cut,up}} |
|---------|----------------------|--------|-------------------|-------------------|
| Mg      | 0.35                 | 0.17   | 0.34              | 0.34              |
| Al      | 0.60                 | 0.29   | 0.51              | 0.50              |
| Si      | 0.37                 | 0.12   | 0.24              | 0.18              |
| Ca      | 0.15                 | 0.02   | 0.05              | 0.02              |
| Ti      | 0.32                 | 0.20   | 0.21              | 0.20              |
| Fe      | 0.18                 | 0.18   | 0.18              | 0.18              |
| Ni      | 0.30                 | 0.13   | 0.13              | 0.13              |
| O       | 0.18                 | 0.18   | 0.37              | 0.35              |
| C       | 0.11                 | 0.12   | 0.13              | 0.13              |

Note—Expected abundances in the secondary atmosphere contaminated with nucleosynthetic products of metal-rich explosion models for two different mass cuts and symmetries, presented in Figs. 12 and 13.

\( ^{a} \) Expected abundances of the secondary star.

\( ^{b} \) Observed abundances of the secondary star in XTE J1118+480.

\( ^{c} \) Initial abundances assumed for the secondary star in XTE J1118+480 (see text). The initial C and O abundances of the metal-rich models were adopted from Ecuvillon et al. (2004, 2006).

\( ^{d} \) \( M_{\text{cut,low}} \) and \( M_{\text{cut,up}} \) are the lower and upper mass cuts adopted in the model computations. See the exact values in the legends of Figs. 12 and 13.
observed abundances, extensive mixing processes are not required. In addition, the non-spherically symmetric ejection of the mass in the explosion could provide the kick that the system needs to change its orbit from the Galactic plane to the current orbit. Therefore, the element abundances in the secondary star and the kinematics of this system strongly suggest that the binary system XTE J1118+480 formed in the Galactic disk (probably the thin disk) and was then kicked toward the Galactic halo, most probably by asymmetric mass ejection in an asymmetric supernova or hypernova explosion that gave rise to the black hole in this system.

The elements O and C, for which we provide the expected abundances in Tables 5 and 6, could be studied in future investigations, probably from CO and OH bands in the near-infrared. This would help to recognize the operation of the CNO cycle on the surface the secondary star, proposed by Haswell et al. (2002), and possible processes of rotation-induced mixing during the evolution of the massive star.

6. CONCLUSIONS

We have presented Keck II ESI medium-resolution spectroscopy of the black hole binary XTE J1118+480. The individual spectra of the system allow us to derive an orbital period of $P = 0.16995 \pm 0.00012$ days and a radial velocity semi-amplitude of $K_2 = 708.8 \pm 1.4$ km s$^{-1}$. The implied updated mass function is $f(M) = 6.27 \pm 0.04 M_{\odot}$, consistent with (but more precise than) previous values reported in the literature. Inspection of the high-quality averaged spectrum of the secondary star provides a rotational velocity of $v \sin i = 100_{-11}^{+3} \text{ km s}^{-1}$ and hence a binary mass ratio $q = 0.027 \pm 0.009$. The derived radial velocity, $\gamma = +2.7 \pm 1.1$ km s$^{-1}$, of the center of mass of the system agrees, at the $3 \sigma$ level, with the results of previous studies.

We have performed a detailed chemical analysis of the secondary star. We applied a technique that provides a determination of the stellar parameters, taking into account any possible veiling from the accretion disk. We find $T_{\text{eff}} = 4700 \pm 100$ K, $\log g (\text{cm s}^{-2}) = 4.6 \pm 0.3$, $[\text{Fe/H}] = 0.18 \pm 0.17$, and a disk veiling (defined as $F_{\text{disk}}/F_{\text{total}}$) of $\sim 40\%$ at 5000 Å, decreasing toward longer wavelengths.

We have provided further details on the abundances of Mg, Al, Ca, Fe, Ni, and Li already reported in González Hernández et al. (2006), and we determined new element abundances of Si and Ti. The chemical abundances are typically higher than solar, and in some cases they are slightly enhanced (e.g., Mg, Al, and Si) in comparison with the abundances of these elements in stars of the solar neighborhood having similar iron content.

The present location and kinematics of this binary system suggested that it could have originated in the Galactic halo. However, the chemical abundances strongly indicate that the black hole formed as a consequence of a supernova or hypernova explosion that occurred within the binary system. This explosive event must have either provided a kick to the system if it was formed in the thin disk or enriched significantly the atmosphere of the secondary star if the system formed in the thick disk or halo.

We have explored a variety of supernova/hypernova explosion models for different metallicities, He core masses, and geometries. We compared the expected abundances in the secondary star after contamination from nucleosynthetic products from different initial metallicities of the secondary star ($-2.2 < [\text{Fe/H}] < 0.2$), to investigate the formation region in the Galactic halo, thick disk, or thin disk. Metal-poor explosion models ($Z = 0$ and $Z = 0.001$) were not able to fit the observed abundances, since they produce inappropriate ratios between $\alpha$-elements and iron-peak elements, and they are extremely sensitive to the adopted mass cut. This comparison probably rules out an origin in the Galactic halo for this black hole binary.

For the thick-disk scenario, we carefully inspected the model predictions, and although they provide better fits to the observed abundances, they require substantial fallback (up to $5.5 M_{\odot}$) and very efficient mixing processes between the inner layer of the explosion and the ejecta. We thus conclude that this scenario is unlikely.

Metal-rich, spherically symmetric models for the thin-disk scenario are able to fairly reproduce the observed abundances, although they do not easily provide the energy required to launch the system from the Galactic plane to its current halo orbit.
Finally, non-spherically symmetric models produce excellent agreement with the observed element abundances in the secondary star without invoking extensive fallback and mixing. In addition, asymmetric mass ejection would naturally provide the kick to expel this binary system from its birthplace in the Galactic thin disk, which seems to be the most plausible explanation for the origin of this halo black hole X-ray binary.

We thank Keichi Maeda for providing us with his aspherical explosion models, and for helpful discussions. We are grateful to Tom Marsh for the use of the MOLLY analysis package. The W. M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California, and NASA; it was made possible by the generous financial support of the W. M. Keck Foundation. This work has made use of the Vienna Atomic Line Database and IRAF facilities. J. I. G. H. acknowledges support from European Commission contract MEXT-CT-2004-014265 (CIFIST). Additional funding was provided by the Spanish Ministerio de Educacion y Ciencia, project AYA 2005-05149, as well as by US National Science Foundation grants AST 03-07894 and AST 06-07485 to A. V. F.

REFERENCES

Allende Prieto, C., Barklem, P. S., Lambert, D. L., & Cunha, K. 2004, A&A, 420, 183
Allende Prieto, C., Beers, T. C., Wilhelm, R., Newberg, H. J., Rockosi, C. M., Yanny, B., & Lee, Y. S. 2006, ApJ, 636, 804
Al-Naimiy, H. M. 1978, Ap&SS, 53, 181
Beer, M. E., & Podsia{łowski, P. 2002, MNRAS, 331, 351
Bensby, T., Feltzing, S., & Lundström, I. 2003, A&A, 410, 527
Bensby, T., Feltzing, S., Lundström, I., & Iliev, I. 2005, A&A, 433, 185
Benz, W., & Hills, J. G. 1992, ApJ, 389, 546
Bruzual, G. M., & Friel, T. W. 1989, ApJS, 49, 447
Cayrel, R., et al. 2004, A&A, 416, 1117
Chen, B. 1997, ApJ, 491, 181
D’Antona, F., & Mazzitelli, I. 1994, ApJS, 90, 467
Eccvillon, A., Israelian, G., Santos, N. C., Mayor, M., Villar, V., & Bihain, G. 2004, A&A, 426, 619
Eccvillon, A., Israelian, G., Santos, N. C., Shchukina, N. G., Mayor, M., & Rebolo, R. 2006, A&A, 445, 633
Frontera, F., et al. 2001, ApJ, 561, 1006
Gilbert, D. M., Balman, Ş., Kuzio{łgu, U., Yilmaz, A., Kalemci, E., & Tomskis, J. 2006, ApJ, 642, 438
Gillon, G., Israelian, G., Eccvillon, A., Santos, N. C., & Mayor, M. 2006, A&A, 449, 723
González Hernández, J. I., Rebolo, R., & Israelian, G. 2008, A&A, 478, 203
González Hernández, J. I., Rebolo, R., Israelian, G., Casares, J., Maeda, K., Bonifacio, P., & Molaro, P. 2005, ApJ, 630, 495
González Hernández, J. I., Rebolo, R., Israelian, G., Casares, J., Meade, A., & Meynet, G. 2004, ApJ, 609, 988
González Hernández, J. I., Rebolo, R., Israelian, G., Haral{tas, E. T., Filippenko, A. V., & Chornock, R. 2006, ApJ, 644, L49 (Paper 1)
Grevesse, N., Noels, A., & Sauval, A. J. 1996, in ASP Conf. Ser. 99, Cosmic Abundances, ed. S. S. Holt & G. Sonneborn (San Francisco: ASP), 117
Gualandris, A., Colpi, M., Portegies Zwart, S., & Possenti, A. 2005, ApJ, 618, 845
Haswell, C. A., Hynes, R. I., King, A. R., & Schenker, K. 2002, MNRAS, 332, 928
Hills, J. G. 1983, ApJ, 267, 322
Hynes, R. I., Robinson, E. L., & Bitter, M. 2005, ApJ, 630, 405
Israelian, G., Rebolo, R., Basri, G., Casares, J., & Martin, E. L. 1999, Nature, 401, 142
Jonsell, K., Edvardsson, B., Gustafsson, B., Magain, P., Nissen, P. E., & Asplund, M. 2005, A&A, 440, 321