New clues on the nature of the companion to PSR J1740-5340 in NGC6397 from XSHOOTER spectroscopy. [1]

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ABSTRACT

By using XSHOOTER spectra acquired at the ESO Very Large Telescope, we have studied the surface chemical composition of the companion star to the binary millisecond pulsar PSR J1740-5340 in the globular cluster NGC 6397. The measured abundances of Fe, Mg, Al and Na confirm that the star belongs to the cluster. On the other hand, the measured surface abundance of nitrogen ([N/Fe]= $+0.53 \pm 0.15$ dex) combined with the carbon upper limit ([C/Fe]< -2 dex) previously obtained from UVES spectra allow us to put severe constraints on its nature, strongly suggesting that the pulsar companion is a deeply peeled star. In fact, the comparison with theoretical stellar models indicates that the matter currently observed at the surface of this star has been processed by the hydrogen-burning CN-cycle at equilibrium. In turn, this evidence suggests that the pulsar companion is a low mass (~ 0.2 $M_\odot$) remnant star, descending from a ~ 0.8 $M_\odot$ progenitor which lost $\sim 70-80\%$ of its original material because of mass transfer activity onto the pulsar.

Subject headings: pulsars: individual (PSR J1740-5340)— globular clusters: individual (NGC 6397)— stars: neutron

1. Introduction

The dense and dynamically active environment typical of Galactic globular clusters (GCs) provide the ideal conditions for the formation and evolution of stellar exotica, such

[1]Based on data taken at the ESO, within the observing programs 085.D-0377(A) and 087.D-0716(A).

as blue straggler stars, interacting binaries and millisecond pulsars (hereafter MSPs; see Bailyn 1995; Bellazzini et al. 1995; Ferraro et al. 1995, 2009, 2012). In particular MSPs are generated in binary systems containing a neutron star, which is eventually spun-up through mass accretion from an evolving companion. The final state therefore is a deeply peeled or even exhausted star (as a white dwarf) orbiting a rapidly spinning pulsar.

The MSP J1749-5340, discovered in the GC NGC 6397 (D'Amico et al. 2001a), belongs to a binary system with a orbital period of $\sim$ 1.35 days. At 1.4 GHz radio frequency it shows eclipses for about 40% of the orbital period, likely due to matter released from the companion (D'Amico et al. 2001b), which probably is also responsible for its X-ray emission (see Grindlay et al. 2001). The companion star (hereafter, COM J1740-5340) was identified by Ferraro et al. (2001) as a variable star with a luminosity comparable to that of the Main Sequence (MS) Turnoff and an anomalously redder color (see right panel in Figure 1). The shape of its light curve suggests that it is tidally distorted by the interaction with the pulsar (Ferraro et al. 2001; Kaluzny et al. 2003).

In virtue of its brightness ($V \sim 16.6$), COM J1740-5340 represents one of the rare cases where spectroscopy of a GC MSP companion can be successfully performed, accurately investigating its kinematical and chemical properties. Indeed, a detailed study of the companion radial velocity curve was performed by Ferraro et al. (2003) and, once combined with the PSR radial velocity curve, it allowed to derive the mass ratio of the system ($M_{\rm PSR}/M_{\rm COM} = 5.85 \pm 0.13$). In turn, this constrained the companion mass in the range 0.22 $M_\odot \leq M_{\rm COM} \leq 0.32$ $M_\odot$(Ferraro et al. 2003; Kaluzny et al. 2003). In addition, also a chemical analysis has been performed, highlighting *(a)* a complex structure of the Hα profile, well reproduced by two different emission components (Sabbi et al. 2003a), *(b)* the unexpected detection of a He I line, suggesting the existence of a hot (T>10000 K) region located on the stellar hemisphere facing the MSP (Ferraro et al. 2003), and *(c)* some anomalous chemical patterns (for Li, Ca and C) with respect to the GC chemical composition (Sabbi et al. 2003b).

Several hypothesis have been proposed to explain the nature of this system and find a coherent picture for the observational evidence collected (Possenti 2002; Burderi et al. 2002; Orosz & van Kerkwijk 2003). In particular, two possible origins for COM J1740-5340 can be advanced: *(1)* it is a low-mass (< 0.3 $M_\odot$), MS star perturbed by the pulsar; *(2)* it is a *normal* star (at the Turnoff or slightly evolved, according to its luminosity), deeply peeled by mass loss down to the present mass.

Following the suggestions of Ergma & Sarna (2003), the CN surface abundances are an ideal tool to discriminate between the two proposed scenarios: in fact, if it is a perturbed MS star, its C and N abundances will be unmodified with respect to the pristine cluster chemical composition. On the other hand, if it is a peeled star, its chemical composition will show the signatures of H-burning CN-cycle (in particular, a decrease of ^{12}C and an increase of ^{14}N) [2]. A first evidence in favour of the latter scenario has been provided by the significant lack of C in COM J1740-5340, through the analysis of UVES@VLT high-resolution spectra (Sabbi et al. 2003b). Unfortunately, however, those spectra do not allow to measure the N abundance. In this paper we present XSHOOTER spectroscopic observations of COM J1740-5340, focussing on the N abundance.

2. Observations

Observations of COM J1740-5340 were secured with the XSHOOTER spectrograph at the ESO-VLT. A second target (hereafter MS1) was included in the same slit and used as comparison star. This is a MS star with $V_{606} = 17.28$, located at $\sim 1.3''$ from the main target (see Figure 1, right panel; two other objects lie within the slit, their faintness, $V_{606} > 19.5$). A first observing run has been performed in June 2010, enabling simultaneously the UVB ($\sim$ 3300-5500 Å) and the VIS ($\sim$5500-10000 Å) channels of XSHOOTER. The adopted slit width was $0.8''$ (R=6200) and $0.7''$ (R=11000) for the UBV and VIS channels, respectively, and the exposure time was 1200 s in both cases. To increase the SNR in the region around the NH band ($\sim$3360 Å), a second observation has been secured in July 2011, using only the UVB channel, with the same slit width and with an exposure time of 2700 s.

The data reduction was performed with the XSHOOTER ESO pipeline, version 2.0.0, including bias subtraction, flat-fielding, wavelength calibration, rectification and order merging. Because the pipeline does not support efficiently the spectral extraction for many sources in the same slit, this task was performed manually with the IRAF package *apall* in optimal extraction mode. The final spectra have SNR=50-100 for COM J1740-5340, and SNR=40-70 for MS1.

3. Chemical analysis

The chemical abundances of Fe, C, N, Na, Al and Mg have been derived through a χ^2-minimization between the observed spectral features and a grid of synthetic spectra computed with different abundances for each species, following the procedure described in

[2]Note that this is also the chemical signature used by Ferraro et al. (2006) to infer a mass-transfer origin for a sub-sample of blue straggler stars in 47 Tucanae.

Mucciarelli et al. (2012). With respect to the traditional method of the equivalent widths, this approach reduces the difficulties in the continuum location, a critical task in the analysis of low-resolution spectra because of the severe line blanketing conditions.

For the analysis of COM J1740-5340 we adopted the atmospheric parameters (T_{eff}= 5530 K, log g= 3.46 and v_{turb}= 1.0 km/s) derived by Sabbi et al. (2003b). For MS1 we derived T_{eff}= 6459 K and $\log g$ = 4.44 by comparing the position of the star in the CMD with a theoretical isochrone from the BaSTI dataset (Pietrinferni et al. 2006) with Z=0.0003 (corresponding to [Fe/H]=–2.1), α-enhanced chemical mixture, and an age of 12 Gyr, assuming the reddening and the distance modulus by Ferraro et al. (1999). The photometric T_{eff} is confirmed by the analysis of the wings of the Hα line (the T_{eff} of COM J1740-5340 has been derived from the Hα wings, thus we can considered the T_{eff} of the two objects on the same scale). For the microturbulent velocity we assumed 1 km s^{-1}, that is a reasonable value for unevolved low-mass stars (Gratton et al. 2001).

The synthetic spectra have been computed with the SYNTHE code by R. L. Kurucz (Sbordone et al. 2004), including all the atomic and molecular transitions listed in the Kurucz/Castelli line list[3]. All the synthetic spectra have been convolved with a Gaussian profile to reproduce the appropriate spectral resolution. The synthetic spectra used for the analysis of COM J1740-5340 have been also convolved with a rotational profile with $v \sin i$= 50 km s^{-1}, (Sabbi et al. 2003b). Instead, for MS1 no additional rotational velocity is added, according to the very low values (<3-4 km s^{-1}) typically measured in unevolved low-mass stars (Lucatello & Gratton 2003). The model atmospheres have been calculated with the ATLAS9 code (Castelli & Kurucz 2004), assuming with [M/H]= -2.0 dex and α-enhanced chemical composition (according to the analysis by Sabbi et al. 2003b).

The spectral lines for the analysis have been selected through the detailed inspection of the synthetic spectra, considering only those transitions that are unblended at the XSHOOTER resolution. A total of 15 and 13 Fe I lines have been selected in COM J1740-5340 and in MS1, respectively. The nitrogen abundances were derived by fitting the bandhead of the A-X (0-0) and (1-1) transitions located at 3360 Å and 3370 Å, respectively. The inspection of the solar-flux spectrum by Neckel & Labs (1984) suggested that we need to decrease by 0.5 dex the Kurucz log gf, in order to properly reproduce the solar N abundance. The carbon abundances were derived from the CH G-band at 4300 Å. The Kurucz log gf for the CH transitions were decreased by 0.3 dex, in order to reproduce the G-band observed in the solar-flux spectrum by Neckel & Labs (1984), as discussed in Mucciarelli, Salaris & Bonifacio (2012). Aluminum abundances were derived from the UV

[3]http://wwwuser.oat.ts.astro.it/castelli/linelists.html

resonance line at 3961 Å, applying a non-LTE correction of +0.7 dex for both targets, according to the calculations of Andrievsky et al. (2008). To derive the sodium abundance, we used the Na doublet at 8183-8194 Å: these lines fall in a spectral region severely contaminated by telluric features. Despite the accuracy of the telluric subtraction (performed with the IRAF task *telluric* by adopting as template the spectrum of an early-type star observed during the observing runs), the radial velocities of the two stars prevent a total deblending between the Na lines and the telluric features. For both stars we therefore provide only upper limits for the Na abundance, including the non-LTE corrections by Lind et al. (2010).

Abundance uncertainties have been estimated by adding in quadrature the errors obtained from the fitting procedure and those arising from the atmospheric parameters. The uncertainties in the fitting procedure have been estimated by resorting to MonteCarlo simulations. Uncertainties due to atmospheric parameters are calculated by varying one parameter at a time while keeping the other ones fixed, and repeating the analysis.

4. Results

Table 1 lists the chemical abundances derived for COM J1740-5340 and MS1, together with their total uncertainties. The iron content of MSP companion is [Fe/H]= -2.00 ± 0.12 dex, in agreement with both the iron abundance of MS1 ([Fe/H]= -1.93 ± 0.18 dex) and previous estimates of the cluster metallicity (see e.g. Carretta et al. 2009; Lovisi et al. 2012). In addition, COM J1740-5340 and MS1 show very similar values of the Na, Mg and Al abundances. These elements are involved in the chemical anomalies usually observed in GCs (Gratton et al. 2012) and are explained as due to two or more bursts of star formation in the early phases of the cluster evolution (see D'Ercole et al. 2008). In particular, given the ranges of values measured in unevolved stars both in NGC 6397 (Gratton et al. 2001; Carretta et al. 2005; Pasquini et al. 2008) and in GCs of similar metallicity (Carretta et al. 2009), the [C/Fe], [Mg/Fe] and [Al/Fe] abundance ratios, as well as the upper limit of [Na/Fe] derived for MS1 suggest with this object belongs to the first generation of stars [4]. In turn, the observed chemical similarity indicates that this is likely the case also for COM J1740-5340.

The [N/Fe] upper limit obtained for MS1 is also consistent with what expected for the first stellar generation (see Carretta et al. 2005), while the value measured for COM J1740-

[4]Lind et al. (2009) derive for Turnoff stars in NGC 6397 temperatures lower than those predicted by the BaSTI isochrone. We repeated the analysis of MS1 decreasing T_{eff} by 250 K, in order to match the T_{eff} scale by Lind et al. (2009). The differences in the derived [C/Fe] and [N/Fe] are smaller than 0.2 dex and do not change our conclusions about this star.

5340 ([N/Fe]= $+0.53 \pm 0.15$ dex) is significantly larger. Fig. 2 shows the observed spectrum of COM J1740-5340 in the region around the NH band, compared with synthetic spectra calculated with different values of [N/Fe]. Besides the best-fit synthetic spectrum (thick solid line), two other spectra are shown: one has been computed assuming [N/Fe]= 0 dex, consistent with what expected on the surface of an unperturbed star and the results obtained for MS1; the other one has [N/Fe]= +1.4 dex, which is the value predicted for the NO-cycle equilibrium (see Sect. 5). Clearly both these additional values are incompatible with the measured abundance. As discussed in Section 5, this provides interesting constraints on the structure and the nature of this star.

Because of the weakness of the G-band only an upper limit for the C abundance of COM J1740-5340 is derived: at the XSHOOTER resolution, we measure [C/Fe]< -1.0 dex. This is compatible with the (more stringent) limit derived by Sabbi et al. (2003b) from high-resolution UVES spectra ([C/Fe]< -2.0 dex), which is therefore adopted in the following discussion. Note that these upper limits are significantly smaller than any C abundance measured in NGC 6397 stars (e.g. Carretta et al. 2005).

5. Discussion

The abundances of C and N measured for COM J1740-5340 are incompatible with the values expected on the surface of an unpeeled MS star. Also, its very low [C/Fe] is incompatible with the C abundances range observed in the cluster (Carretta et al. 2005), excluding that COM J1740-5340 is an unpeeled second generation star. Hence, option (1) discussed in the Introduction can be ruled out. In order to verify the possibility that COM J1740-5340 is, instead, a deeply peeled Turnoff/sub-giant star and to put new constraints on its nature, we compare the derived C and N abundances with the chemical gradients predicted in theoretical stellar models.

We have calculated the evolution of a 0.8 $M_{\odot}$ stellar model, from the pre-MS to the red giant branch phase, using the same code and input physics of the BaSTI models (see e.g Pietrinferni et al. 2004, 2006). We adopted Z=0.0003, Y=0.245, and an α-enhanced metal mixture([α/Fe]=+0.4), which is appropriate for the first generation of stars in Galactic GCs (in particular, we assume [C/Fe]=0 and [N/Fe]=0, also consistently with the abundances measured for MS1). The Turnoff age of the model is 12 Gyr. This value, however, depends on the efficiency of atomic diffusion, which can be (partially or totally) inhibited by additional turbulent mixing (for which an adequate physical description is still lacking). We therefore calculated models both with and without atomic diffusion, finding that they are basically indistinguishable (in the following we therefore presents only the results obtained from models without atomic diffusion). Also the effects of radiative levitation are totally negligible at the metallicity of NGC 6397, because the radiative acceleration on the C and N atoms is always smaller than the gravitational acceleration (see Fig. 3 in Richard, Michaud & Richer 2002) and we therefore do not include them in our models.

Fig. 3 shows the gradients of the [^{12}C/Fe] and [^{14}N/Fe] abundance ratios in the interior of a sub-giant star[5], as a function of the stellar mass, from the center to the surface ($M = 0.8$ M$_\odot$). As apparent, these abundances remain constant along the entire stellar envelope, from the surface, down to the radius including half of the total mass. The fflat chemical profiles at [N/Fe]= +1.4 dex and [C/Fe]~ -1 dex observed in the very central region ($M \lesssim 0.15$ M$_\odot$) are the consequence of the CNO-burning that occurred in the stellar core during the MS evolution. The gradients observed in the intermediate region (0.15 M$_\odot \lesssim M \lesssim 0.4$ M$_\odot$), instead, are due to the ongoing hydrogen burning in a thick shell above the inactive core (with a mass of $\sim$0.11 M$_\odot$). In particular, the most external portion of the shell is mainly interested by the CN-cycle and therefore shows an increase of ^{14}N and a drop of ^{12}C. At 0.18 M$_\odot \lesssim M \lesssim 0.38$ M$_\odot$ the abundances of ^{12}C and ^{14}N reach the equilibrium: C displays its minimum value ([C/Fe]= -2.45 dex) and the N abundance profile shows a *plateau* at [N/Fe]= +0.68 dex. In the innermost portion of the shell the NO-cycle is active, thus producing a further increase of both ^{14}N and ^{12}C, up to the most central values.

The dashed vertical lines in Fig. 3 mark the range of mass profile where the carbon abundance of the stellar model is in agreement with the upper limit ([C/Fe]< -2 dex) derived for COM J1740-5340 (Sabbi et al. 2003b). In this same mass range also the N abundance shows a good agreement between the model prediction and the measured value (black triangle in Fig. 3). Instead the [N/Fe] ratio observed in COM J1740-5340 is incompatible with the abundance ratio predicted in any other region of the stellar model (consistently with what discussed above; see Fig. 2). This evidence strongly suggests that COM J1740-5340 is a star peeled down to the region where the CN-cycle occurs, as a result of heavy mass transfer onto the neutron star.

The C and N abundances allow us to also identify a reasonable mass range for the MSP companion. Fig. 4 shows the behavior of the discussed stellar model in the [C/Fe]–[N/Fe] plane. The light grey box indicates the locus corresponding to the abundances of COM J1740-5340 (taking into account the quoted uncertainties). Clearly, only the portion of the stellar model between 0.17 and 0.28 M$_\odot$ overlaps this region. This mass range is

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[5]It is not easy to identify the evolutionary stage of the star in the scenario of a peeled star. Its position in the CMD (Fig. 1) suggests that the object is a slightly evolved star (see also Burderi et al. 2002), but we cannot exclude that it still belongs to the MS. In any case, its luminosity seems to exclude that it is a giant star.

in very good agreement with the value (0.22-0.32 $M_\odot$; Ferraro et al. 2003) estimated for COM J1740-5340 from the binary system mass ratio (inferred from the radial velocity curve of the companion) and the orbital inclination angle (inferred from the optical light curve). In order to quantify how much the results depend on the evolutionary phase of the star before the onset of heavy mass transfer, we repeated the analysis by using models on the MS, at the base of the Red Giant Branch (RGB), before and after the occurrence of the First Dredge-Up. Following the evolution from the Turnoff to the base of the RGB, the region where the NO-cycle occurs increases in mass, thus reducing the mass range where the model C and N abundances match the observed ones. If the MSP companion was a Turnoff star, COM J1740-5340 should now have a mass between 0.13 and 0.27 $M_\odot$, while the range decreases significantly in case of a RGB star: 0.22-0.28 $M_\odot$ for a star before the First Dredge-Up, and 0.25-0.28 $M_\odot$ for a star after the First Dredge-Up. Note that in all the cases, the upper mass limit remains basically unchanged, confirming a value smaller than 0.3 $M_\odot$, even if the upper limit for the C abundance inferred from the XSHOOTER spectra ([C/Fe]~ -1) is assumed. We finally stress that different assumptions about the initial C and N abundances of the star have the effect of rigidly shifting the model curves in both the planes shown in Figs. 3 and 4.

The evidence presented here adds an important piece of information to properly characterize COM J1740-5340. The analysis of the C and N surface abundances provides a diagnostic of the companion mass which is totally independent of other, commonly used methods, well confirming the previous estimates. In addition, the chemical patterns observed at the surface of COM J1740-5340 solidly confirm that this object is a deeply peeled star, and can be even used to obtain a quantitave evaluation of the amount of mass lost by the star. In fact, our analysis indicates that the entire envelope of the star has been completely removed and the peeling action has extended down to an interior layer where the CN-cycle approximately reached the equilibrium By assuming an initial mass of ~ 0.8 $M_\odot$, we estimate that COM J1740-5340 has lost $\sim 75\%$ of its initial mass during the interaction with the pulsar.

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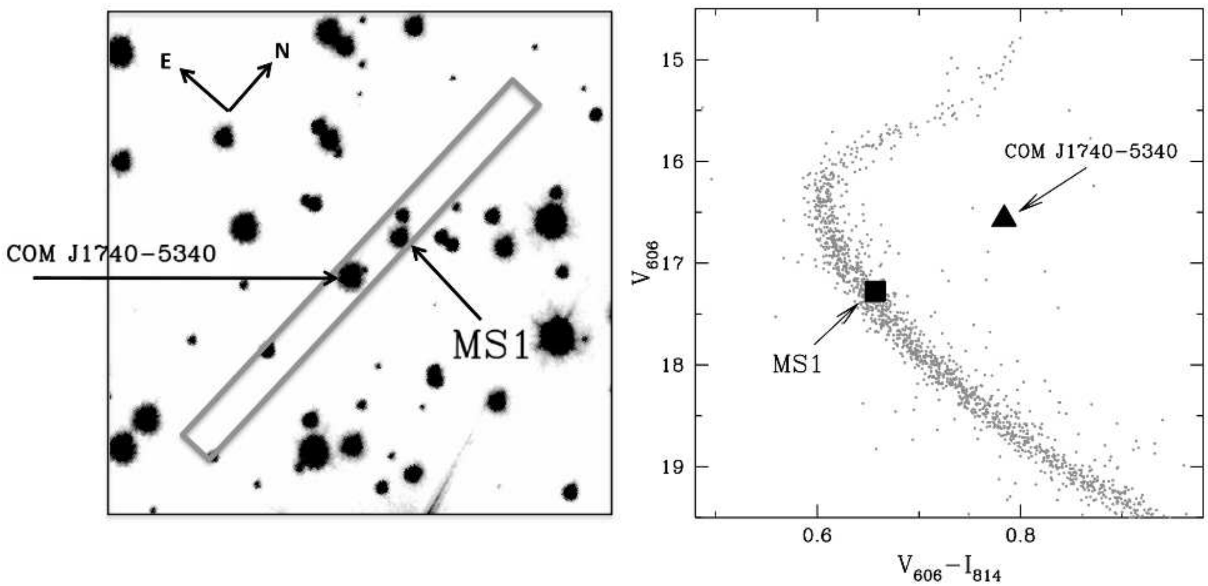

Fig. 1.— *Left panel*: HST-ACS archivial V_{606}-band image with the position of the adopted XSHOOTER slit and the identification of the two targets. *Right panel*: CMD of the radial (R<40 arcsec) region around COM J1740-5340 (Contreras Ramos et al., 2013, in preparation), with marked the position of COM J1740-5340 and MS1.

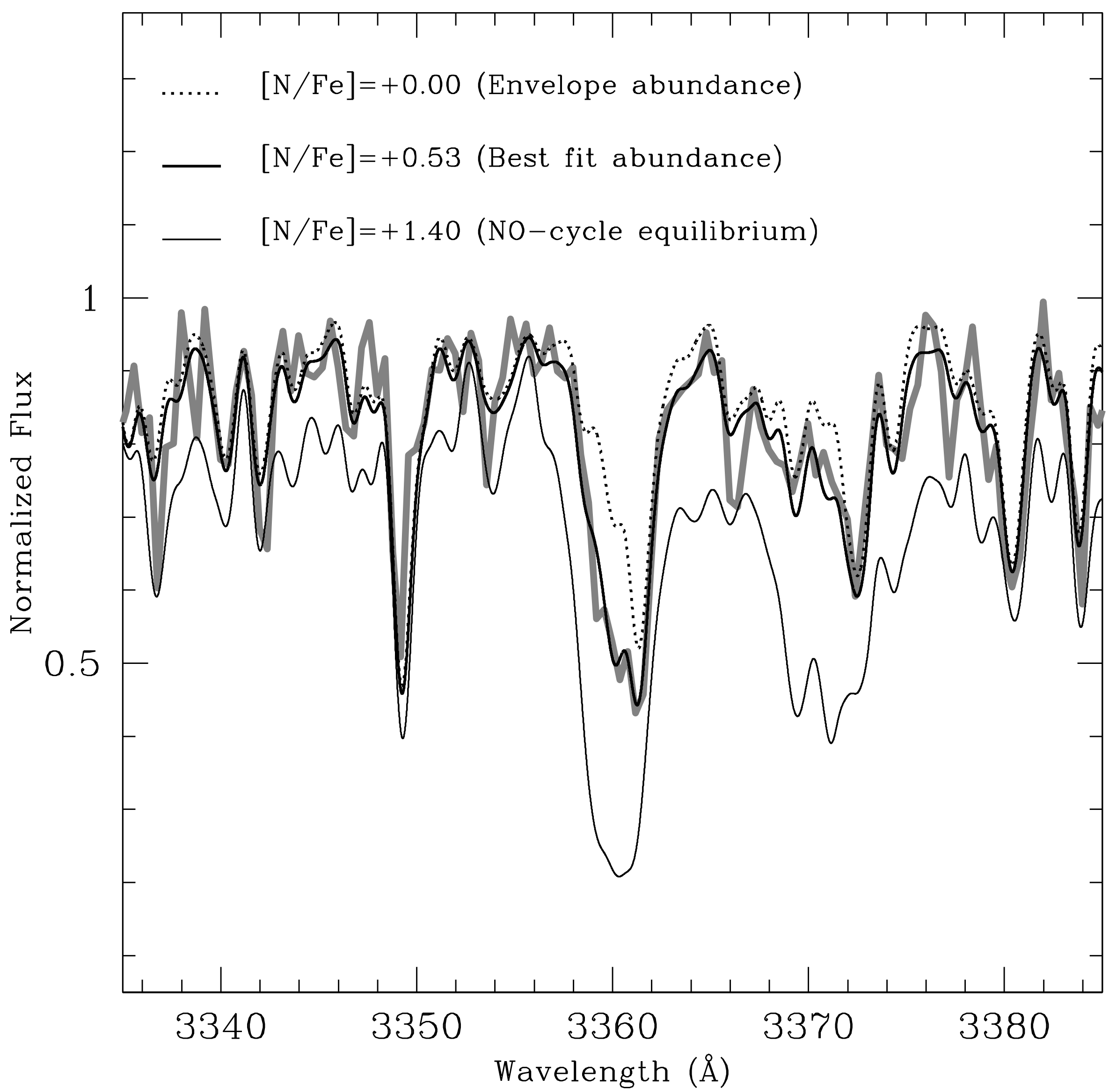

Fig. 2.— Observed spectrum of COM J1740-5340 (thick grey line) in the spectral region around the NH molecular band, with overimposed synthetic spectra calculated with [N/Fe]=+0.0 (corresponding to the stellar envelope abundance, dotted line), +0.53 (best fit abundance, thick solid line), +1.40 (NO-cycle equilibrium abundance, thin solid line).

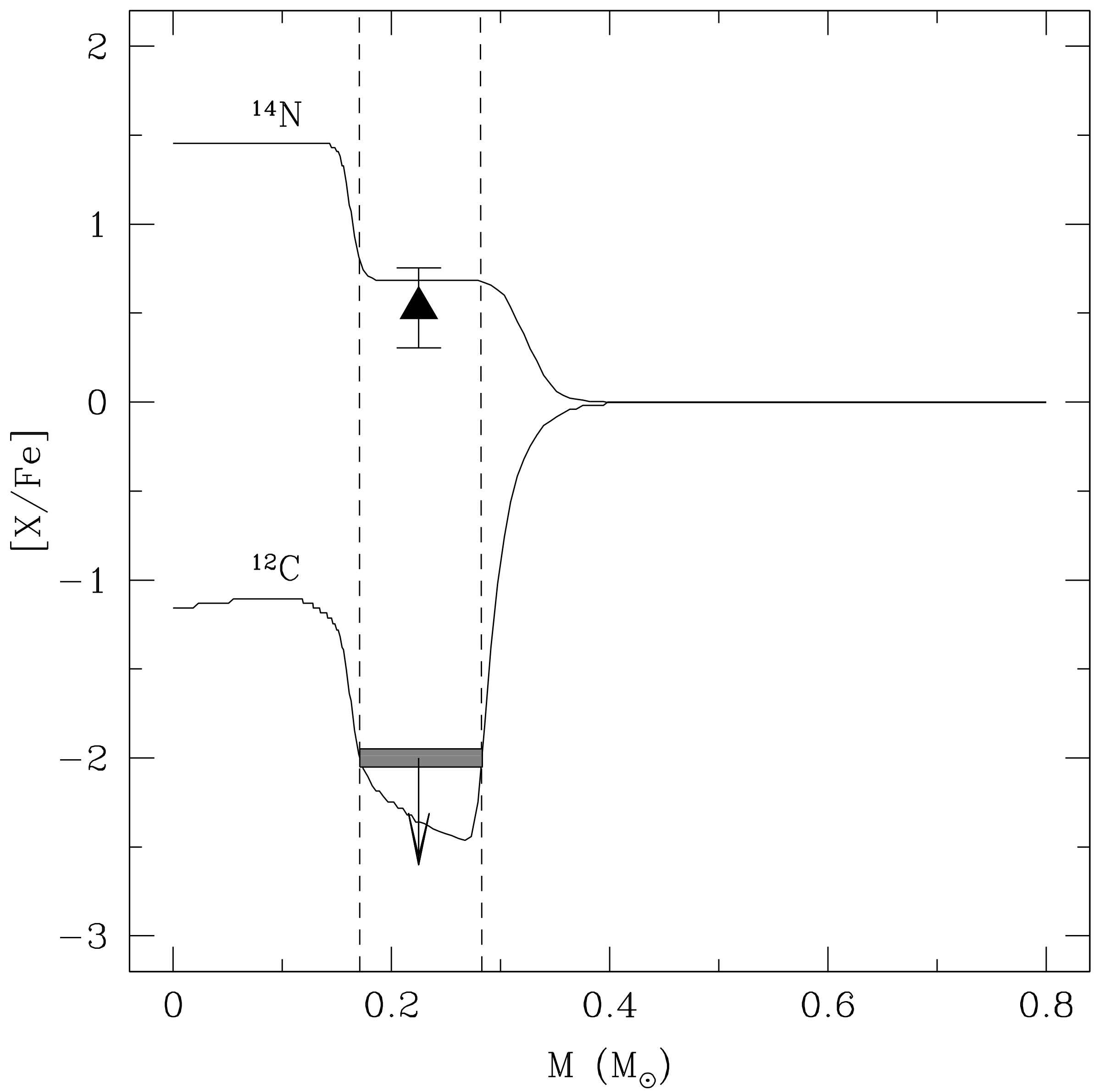

Fig. 3.— Behavior of [X/Fe] abundance ratio for ^{12}C and ^{14}N as a function of the mass, for a stellar model of a sub-giant star with M= 0.8 $M_\odot$, Z= 0.0003 and no atomic diffusion. The black triangle indicates the [N/Fe] measured in COM J1740-5340 while the grey bar is the upper limit for [C/Fe]. The dashed vertical lines mark the mass range defined by the upper limit for [C/Fe].

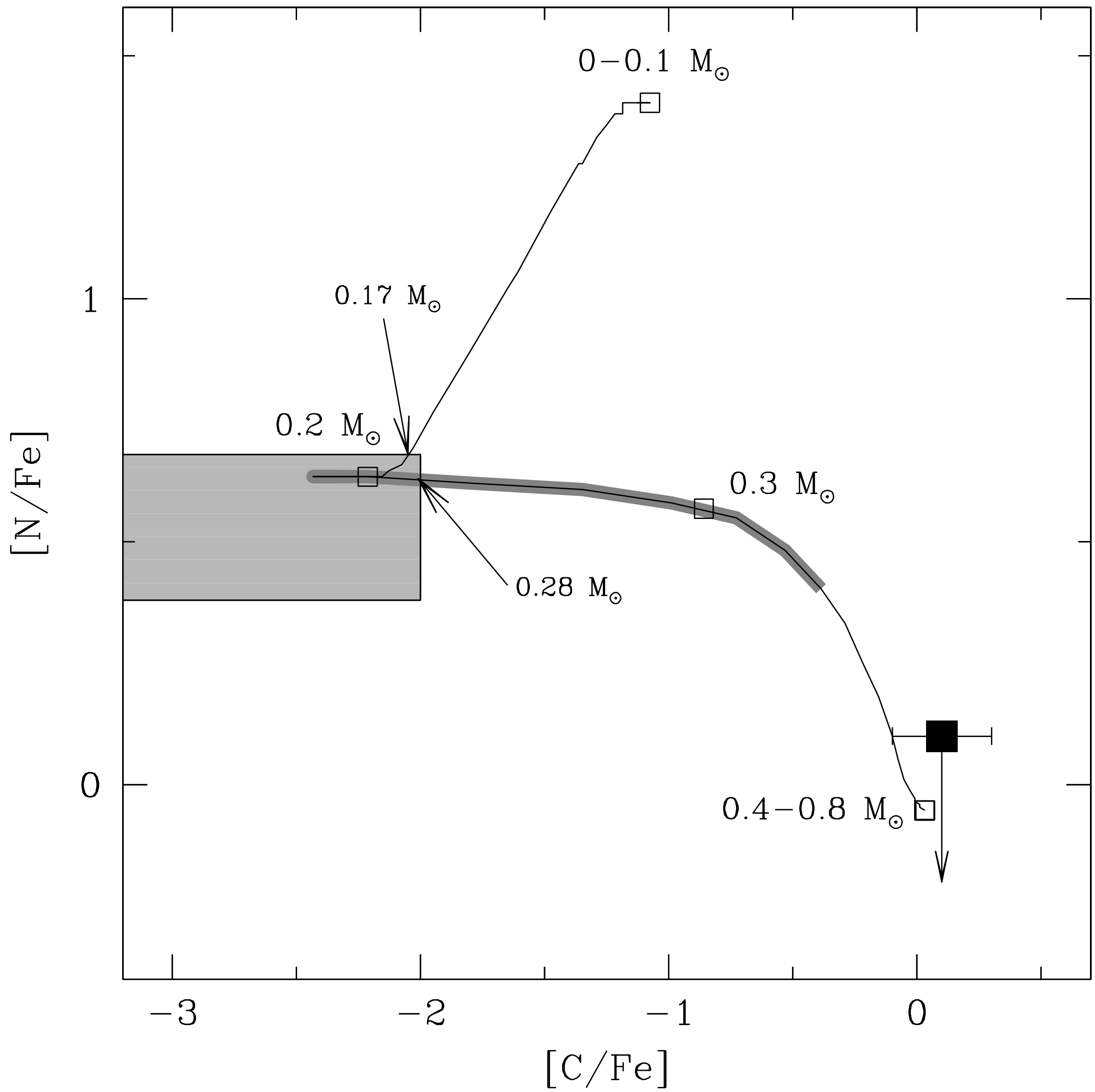

Fig. 4.— Behavior of [N/Fe] as a function of [C/Fe] (thin solid lines) for the same stellar model shown in Fig. 3. Empty squares mark the position of the stellar masses at step of 0.1 $M_{\odot}$. The light grey box indicates the mean locus of [C/Fe] and [N/Fe] of COM J1740-5340. The dark grey region indicates the mass range proposed by Ferraro et al. (2003). The black square marks the position of MS1.

Table 1. Chemical abundances measured for COM J1740-5340 and MS1.

Ratio	COM J1740-5340	MS1
[Fe/H]	-2.00 ± 0.12	-1.93 ± 0.18
[Mg/Fe]	$+0.38 \pm 0.13$	$+0.30 \pm 0.15$
[Al/Fe]	$+0.31 \pm 0.14$	$+0.35 \pm 0.20$
[Na/Fe]	< 0.00	< 0.15
[N/Fe]	$+0.53 \pm 0.15$	$< +0.10$
[C/Fe]	< -1.0	$+0.10 \pm 0.20$

Note. — Reference solar abundances are by Grevesse & Sauval (1998).