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Li ABUNDANCES IN LATE-TYPE COMPANIONS TO NEUTRON STARS AND BLACK HOLE CANDIDATES

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ABSTRACT

Following our recent report of a strong Li I λ6708 resonance line in the secondary of the black hole candidate V404 Cyg, we present here its detection in the quiescent spectrum of the neutron star binary Cen X-4. We obtain, via a spectral synthesis LTE analysis, a surface lithium abundance in the K-type secondary of log $N(\mathrm{Li}) = 3.3 \pm 0.4$. Taking into account non-LTE effects reduces the abundance by 0.2 dex. Using the same analysis, lithium abundances are also derived for the secondaries of the black hole binaries A0620−00, where a lithium detection has very recently been reported, and V404 Cyg.

High lithium abundances appear to be a common feature of late-type secondaries in neutron star and black hole binaries, a result totally unexpected mainly because of post–main-sequence dilution and the mass transfer history of these stars. Convective mixing may cause additional depletion if lithium is taken to layers where it is burnt. In order to counteract the depletion it seems necessary to invoke a process of lithium production. Several mechanisms are plausible: for instance, lithium synthesis in a supernova explosion of the compact primary's progenitor, or an on-going process such as α-α reactions during the repeated strong outbursts that characterize transient X-ray binaries. The spallative mechanism can be tested by future high-resolution γ-ray and optical spectroscopic observations. Implications on the Li enrichment of the Galactic interstellar medium are briefly discussed.

Subject headings: black hole physics — stars: abundances — stars: individual (Centaurus X-4) — stars: neutron

1. INTRODUCTION

Martín et al. (1992, hereafter Paper I) reported the discovery of a strong Li I λ6708 resonance line in the quiescent spectrum of V404 Cyg (GS 2023+338), which is currently considered the best candidate for a stellar mass black hole (Casares, Charles, & Naylor 1992). The serendipitous discovery of Li in V404 Cyg prompted us to initiate an observing program specifically aimed at searching for it in other X-ray binaries. The next two obvious targets were A0620−00 (V616 Mon) because it also harbors a black hole candidate (McClintock & Remillard 1986) and Cen X-4 (V822 Cen) because of its similarity with A0620−00 (McClintock & Remillard 1990) even though its compact primary is a neutron star. These three X-ray binaries are classified as soft X-ray transients (SXTs), sometimes referred to as X-ray novae. They are a subclass of low-mass X-ray binaries (LMXBs) which are characterized by strong outbursts lasting several weeks, followed by long quiescent periods of ∼10–50 yr. In outburst the SXTs can become the brightest X-ray sources in the sky, reaching peak X-ray luminosities in the range 5×10^{37}–10^{39} ergs s^{-1}. Their optical brightness also increases by several orders of magnitude, some of them being identified with historical nova events. On the other hand, while in quiescence, the optical luminosity of SXTs is dominated by the low-mass secondary star, thereby allowing to study its properties. Before attempting to search for Li in A0620−00 we learned of its detection by Marsh, Robinson, & Wood (1994). In this paper we report the detection of a strong Li I feature in the quiescent spectrum of Cen X-4, which is thus the third SXT where Li has been found, and the first one with a known neutron star primary.

Lithium abundances have been measured in a wide variety of astrophysical contexts that have added different pieces to our understanding of the multiple processes leading to its creation and destruction. Its most stable isotope, ^{7}Li, is one of the few elements produced by standard Big Bang nucleosynthesis (BBN), and hence its primordial abundance sets restrictions on the baryonic density of the universe (cf. Reeves 1974; Boesgaard & Steigman 1985). Spite & Spite (1982) found a Li plateau in halo dwarfs and proposed that their average abundance of log $N(\mathrm{Li}) = 2.1$ is the primordial Li abundance resulting from BBN.[1] On the other hand, the Li abundances of the interstellar medium (ISM), presolar nebula (meteorites), young cluster members, and T Tauri stars (TTSs) indicate that the cosmic Li abundance in the Galactic disk is around log $N(\mathrm{Li}) = 3.1$ (cf. Martín et al. 1994) and has remained essentially constant over the last 5×10^9 yr. The importance of Li as a constraint on BBN resides largely on the knowledge of its primordial abundance. If such an abundance is that of the Spites plateau, it follows that the Galactic gas has been enriched in Li by about one order of magnitude.

Several sources of Galactic Li production have been studied in the literature. The Cameron (1955) mechanism was proposed to account for the super Li-rich asymptotic giant branch (AGB) red giants. This process is associated with thermal

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[1] The number density N is defined by log $N(\mathrm{Li}) = 12 + \log(N_{\mathrm{Li}}/N_{\mathrm{H}})$.

1994ApJ...435..791M

pulses during helium-shell flashes. However, the duration of the super Li-rich phase is extremely short (~2000 yr; Iben 1973), and such red giants are indeed very rare (~2%; Abia et al. 1993). It is unclear if they can be responsible for any substantial Li enrichment in the Galaxy. Spallation reactions induced by fast particle collisions with He, C, N, O nuclei have for many years been the favored mechanism of light-element (Li, Be, and B) production in the Galaxy. For some years it was believed that they were responsible for the high Li abundances in TTSs (cf. Fowler, Greenstein, & Hoyle 1962). However, Ryter et al. (1970) showed that it was unlikely that TTSs have enough energy for Li generation. Walker, Mathews, & Viola (1985) were able to account for the present abundances of most light elements by cosmic-ray–induced spallation in the ISM, but they underproduced the abundance of ^{7}Li by a factor of 10. Although other Galactic source sites of ^{7}Li have been proposed, there is no compelling evidence for any of them.

In the following sections, we derive Li abundances in the secondaries of three SXTs, and we examine them in the context of the formation and evolutionary scenarios currently proposed for these binary systems. We argue that a plausible explanation for their high Li abundances is that there is a mechanism of Li production that can counteract the apparently unavoidable secondary's surface Li depletion produced by mass transfer and deep convective mixing.

2. OBSERVATIONS

The lithium detections in V404 Cyg and A0620−00 were presented in Paper I and Marsh et al. (1994), respectively. They were made using co-added spectra taken with the intermediate dispersion spectrograph ISIS at the 4.2 m William Herschel Telescope on La Palma. Both stars were observed with similar configurations, giving a nominal dispersion of 0.74 Å pixel^{-1} (FWHM resolution = 1.5 Å).

In this paper we report new spectroscopic observations of Cen X-4, consisting of 11 1800 s spectra taken at the 3.9 m Anglo-Australian Telescope (AAT) on the nights of 1993 June 24–27. The spectra cover the range $\lambda\lambda$6155–6968 at a nominal dispersion of 0.80 Å pixel^{-1} (FWHM = 1.6 Å). Observing conditions were always photometric, with seeing between 1″ and 1.″5. The data were processed using standard reduction techniques (debiased, flat-fielded, sky-subtracted, and optimally extracted), and each observation was bracketed by a Cu-Ne arc in order to interpolate the wavelength scale. Cross-correlations between the continuum normalized spectra of Cen X-4 and the velocity standard HD 9138 (K4 III) were performed in the range $\lambda\lambda$6155–6520 after masking the λ6282 interstellar feature. We obtained an averaged Doppler-corrected spectrum in the rest frame of the secondary from the sine-wave fit to the radial velocity points. A further analysis, containing improved ephemerides and discussing the orbital evolution of the Hα emission, will be presented elsewhere.

In Figure 1 we show the spectrum of Cen X-4, together with the spectra of V404 Cyg and A0620−00. Note the strong Li I absorption and Hα emission in all of them. In Figure 2 we present the Li I spectral region of Cen X-4 at different orbital phases. The Li feature moves in phase with all the secondary's absorption lines, and thus it must be formed in the stellar photosphere. No equivalent width variations are seen at the level of accuracy of our measurements, and hence we consider the average value of equivalent width given in Table 1 adequate for abundance determination.

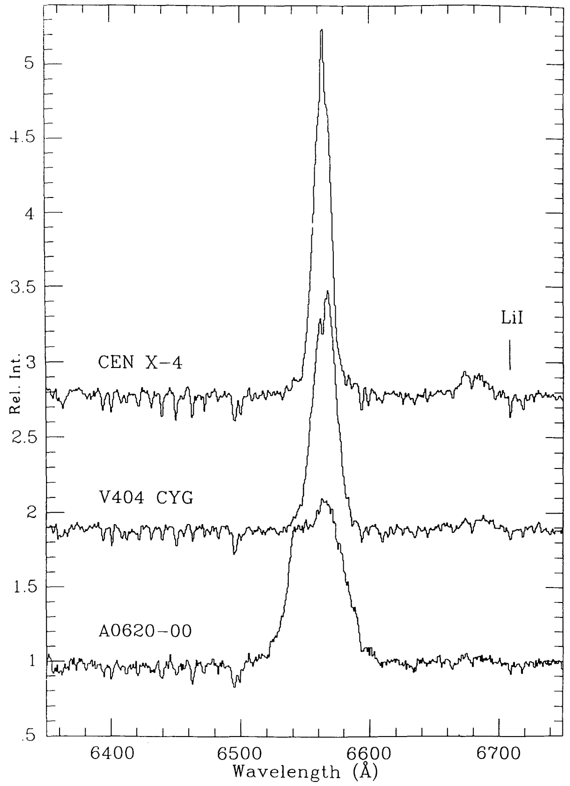

FIG. 1.—Final normalized intermediate-resolution spectra of the three soft X-ray transients in quiescent state considered in this paper. The position of the Li I absorption feature is marked.

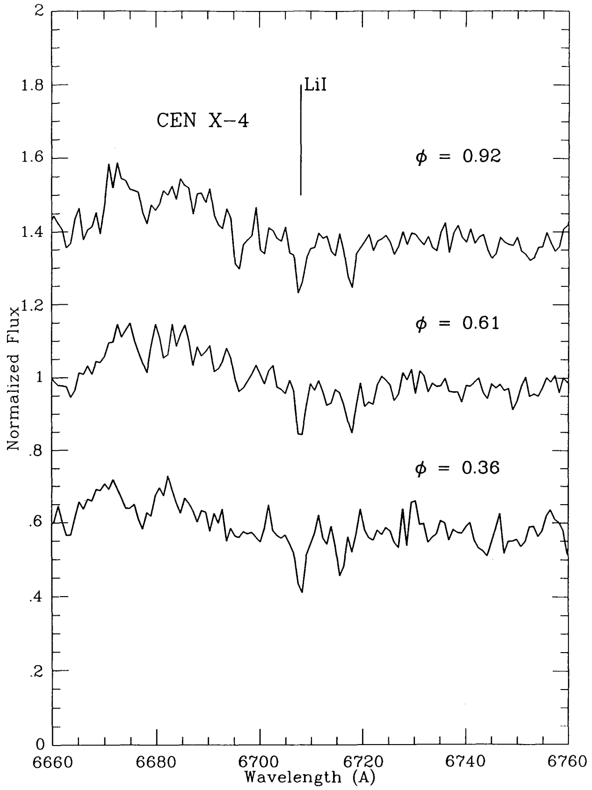

FIG. 2.—Spectrum of Cen X-4 in three different orbital phases. Each spectrum is the sum of three individual AAT spectra. Note that the Li I doublet is present in all of them.

1994ApJ...435..791M

TABLE 1

SURFACE ABUNDANCES OF THREE SXT'S SECONDARIES

NAME	SPECTRAL TYPE	$T_{\rm eff}$ (K)	VEILING	W_λ (Li I) (mÅ)	log N(Li) LTE	log N(Li) NLTE	[Ca/H]
Cen X-4	K5–K7 V	4250	25%	480 ± 65	3.3	3.1	0.0
V404 Cyg	G9–K1 IV	4750	5%	300 ± 50	2.6	2.7	+0.1
A0620−00	K3–K5 V	4500	6%	250 ± 50	2.0	2.1	−0.1

3. ANALYSIS

We have performed a spectrum synthesis analysis of the data. An LTE code developed by Ya. V. Pavlenko (Abel 7; Pavlenko 1991) was used. It includes the contribution of molecular opacities. We employed the grid of LTE model atmospheres provided by Kurucz (1992) and the line list in the Li region of Kurucz & Peytremann (1975). The Li I λ6708 feature was assumed to be entirely due to ^{7}Li, with no contribution by ^{6}Li. Trials using a ^{7}Li/^{6}Li isotopic ratio of 2 were performed, but they gave a slighly worse fit to the observed spectrum. The resolution and signal-to-noise ratio (S/N) of the spectra are too low for making any better estimate of the isotopic ratio. We assumed a priori that we could use solar metallicity atmospheric models, an assumption that proved to be justified by the good fits to the Ca I λ6717 line obtained. The weak Fe I λ6707.4 line and all the known lines blended with the Li I doublet in our spectra were included together in the spectral synthesis, and solar iron abundance was used. A microturbulence value of 2 km s^{-1} was adopted in all computations.

Spectral types for the secondaries are listed in Table 1. They were taken from McClintock & Remillard (1990; Cen X-4), Casares et al. (1993; V404 Cyg), and McClintock & Remillard (1986; A0620−00). The effective temperatures were assigned using the statistical calibrations of spectral type versus $T_{\rm eff}$ and luminosity class by de Jager & Nieuwenhuijzen (1987). The gravities used were of log g = 3.5 for V404 Cyg and log g = 4.0 for the other two secondaries. We derived these values considering the estimates of radii and mass densities available in the literature and assuming that the secondaries fill their Roche lobes.

Although the optical spectrum of SXTs in quiescence is dominated by the secondary, the luminosity from the accretion disk is nonnegligible. It is important to account for such an effect because it veils the photospheric lines of the secondary. For Cen X-4 Chevalier et al. (1989) and McClintock & Remillard (1990) estimated a disk contribution of 25%–30% in the V-band, while Shahbaz, Naylor, & Charles (1993) obtained 25% in R. For V404 Cyg and A0620−00 the disk contribution is smaller; e.g., Marsh et al. (1994) estimated 6% for A0620−00 and Casares et al. (1993) up to 10% for V404 Cyg. We have made our own estimates from the spectra used in this analysis. The method was the same as described by Marsh et al. (1994), and we obtained results consistent with previous values. The final veiling factors adopted are shown in Table 1.

The Li and Ca abundances were changed until a good match was obtained between the synthetic and observed spectra. In Figure 3 we show the final fits to the data. We could not reproduce some lines weaker than those of Ca I and Li I because of the noise fluctuations and moderate spectral resolution of our spectra. Bluewards of the Li I doublet there are two strong Fe I lines, but they are filled by broad He I λ6678 emission. In Table 1 we give the abundances of Li and Ca used in the "best-fit" synthetic spectrum. These synthetic fits were also used to determine the equivalent widths of the Li I line in the spectra of the three systems. The final equivalent widths, incorporating the proper veiling corrections and subtracting the contribution of the Fe I λ6707.4 line (less than 10%), are given in Table 1.

The equivalent widths were used to derive the Li abundance in non-LTE from curves of growth published by Martín et al. (1994). It is remarkable that the high Li abundances found in the secondaries of these three systems are very unusual for stars of such late spectral types. Errors in Li abundance come mainly from uncertainties in temperature (±250 K), veiling (±5%), and equivalent widths (±10%). We estimate a 1 σ error associated with the log N(Li) values of ±0.4 dex. We note that there may be systematic effects not taken into account in this anaylsis. For instance, UV and X-ray irradiation of the stellar surface could affect the formation of the Li doublet. Our Cen X-4 data do not show variations of the Li equivalent width at different orbital phases (different irradiation factors)

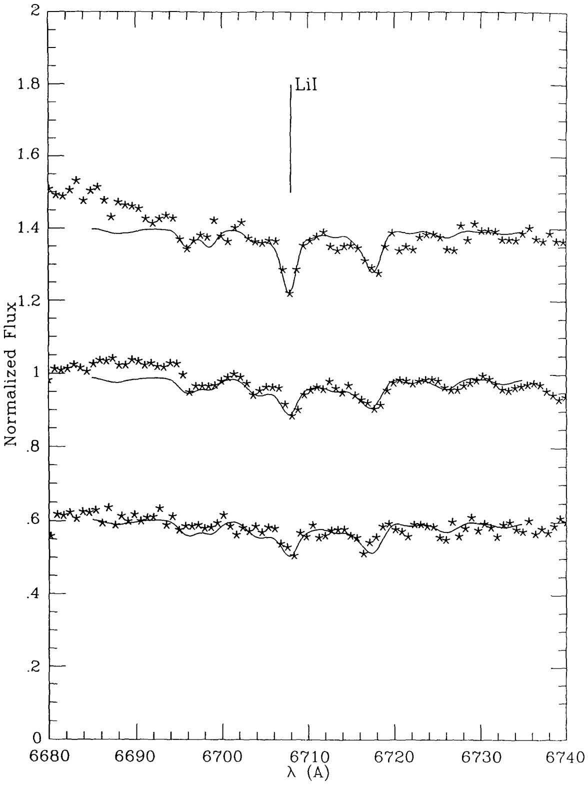

FIG. 3.—Synthetic fits (*solid line*) to the observed spectra (*crosses*) of our three secondaries of compact objects. The Li and Ca abundances derived are given in Table 1.

larger than our error bars. Spectroscopic observations of higher S/N and with a good phase coverage would be needed to search for such an effect.

4. Li AND THE EVOLUTION OF X-RAY TRANSIENTS

Our aim is to examine how the presence of lithium can be understood in the light of current ideas on the formation and evolution of X-ray transients. There are three main scenarios for their formation: (1) Initially the system is a wide binary composed of a very massive primary and a solar-type secondary. When the primary evolves off the main sequence, the secondary is engulfed in the giant's atmosphere, and the system starts a common envelope phase which ends with core collapse and a supernova explosion, or nonexplosive formation of a black hole. It is the most likely scenario for V404 Cyg and A0620−00, but it is unlikely for neutron star binaries, given their reduced ability to retain the secondary after the supernova explosion. (2) Accretion-induced collapse of a massive white dwarf. The time required to form the neutron star in this way is about 1.5×10^9 yr (e.g., Pylyser & Savonije 1988). This seems to be the most likely scenario for a system like Cen X-4. (3) The low-mass secondary is captured by the compact object; this scenario has been proposed to explain the presence of LMXBs in globular clusters.

After formation of the compact remnant, the evolution of the system depends basically on the level of mass transfer from the secondary onto the primary. Possible driving mechanisms are angular momentum losses, X-ray heating, a stellar wind, and nuclear evolution of the secondary. V404 Cyg is well explained by the "stripped giant" model, where the secondary has a helium core and hydrogen-shell burning drives the Roche-lobe overflow (King 1993). Chevalier et al. (1989) considered the possibility that the secondary of Cen X-4 is a dwarf that underfills its Roche lobe, and so mass transfer should be due to a wind. However, McClintock & Remillard (1990) and Shahbaz et al. (1993) have shown that Cen X-4 has too low density to be a main-sequence dwarf, and conclude that it is probably a subgiant that nearly fills its Roche lobe. Ellipsoidal modulations in the light curves of V404 Cyg (Wagner et al. 1992) and A0620−00 (Haswell et al. 1993) provide evidence that their secondaries also fill their Roche lobes. Furthermore, the present secondary mass of A0620−00 is constrained by observations to be in the range $0.2 \leq M_c \leq 0.4$ (Marsh et al. 1994). This is in good agreement with the models of Pylyser & Savonije (1988) who predicted an age for the system larger than 10^9 yr and a global mass loss of more than half of its initial mass.

Lithium is easily destroyed in stellar interiors by (p, α) reactions. The low-mass secondaries of SXTs are thought to come from more massive stars ($M \geq 1\ M_\odot$), which can only preserve some Li in a very thin external region. When they evolve to the subgiant branch, the convection zone becomes larger, and Li is diluted by a large factor (Iben 1967). In addition, the secondaries start to transfer a large amount of mass onto the compact object. Therefore, we are seeing regions of the stars that were originally deep inside. Several works (Hobbs, Iben, & Pilachowski 1989; Swenson & Faulkner 1992) have shown that a mass loss of only 0.05 $M_\odot$ from a main-sequence solar-mass star leads to a surface Li depletion of a factor 10. It is obvious that mass transfer from the SXT's secondaries causes surface Li depletion. Determination of the depletion rate requires proper modeling which takes into account their peculiar subgiant nature and mass loss through Lagrangian points. Convective mixing may be a mechanism of further Li depletion if the base of the convection zone reaches temperatures of about 2.4×10^6 K, as happens in main-sequence K-type stars (e.g., Thorburn et al. 1993). The secondaries of SXTs are tidally locked, and hence convective depletion may be inhibited for instance by reducing the angular momentum transport in the base of the convection zone. Nevertheless, tidally locked binaries in the Hyades have experienced large Li depletion, albeit slightly less (by about 0.4 dex) than their single counterparts (Thorburn et al. 1993).

New observations of late-type secondaries in tidally locked cataclysmic binaries, like GK Per and SS Cyg, have shown a dramatic absence of Li. These secondaries orbit white dwarfs and have periods and spectral types similar to the secondaries of A0620−00 and Cen X-4. We will present these results in a forthcoming paper (Martín et al., in preparation), but it is worth advancing them here because they support our argument that the net effect of dilution, mass loss, and convection is to deplete Li in the secondaries of SXTs. Therefore, we are led to discuss the possibility that a mechanism of production is responsible for the high Li abundances observed. We note that a definitive proof of Li production would be to detect a system with an abundance much higher than the cosmic value. Cen X-4 may have a Li abundance greater than cosmic, but the uncertainties of our analysis currently preclude such a conclusion. Until a new SXT secondary is found with log $N(\mathrm{Li}) \gg 3$, or a better analysis of Cen X-4 resolves whether or not its Li abundance is higher than cosmic, the discussion that follows on Li production mechanisms remains speculative. However, we believe it is warranted as such processes are a plausible explanation of our results.

5. Li PRODUCTION AROUND COMPACT OBJECTS?

A very high Li abundance could have been produced early in the life of the SXTs as a result of particle reactions in supernovae (Dearborn et al. 1989; Woosley et al. 1990), or in Thorne-Zytkow objects as suggested by Podsiadlowski, Cannon, & Rees (1994). It could also be produced after the formation of the compact object by collisions of α particles (accelerated in its vicinity) with helium nuclei ejected during the presupernova evolution of the progenitor (Clayton & Dwek 1976). In these frameworks, the systems would originally have a higher Li abundance than presently observed, which would have been diminished by the processes discussed previously. We cannot rule out this possibility, but neither can we favor one of them because the nature of the compact objects in our three SXTs are very different (two probable black holes and one neutron star). The properties of the secondaries are different as well (one early K-type stripped giant and two late K-type subgiants), and their orbital periods range from 0.32 days for A0620−00 to 6.47 days for V404 Cyg. All these differences suggest that these SXTs have rather different origins and different evolutionary histories.

Alternatively to the hypothesis of early Li enrichment, we deem it convenient to consider a process of ongoing Li production in SXTs, which may be necessary if the total depletion is large enough to reduce Li below our observed abundances. The Cameron mechanism [$^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}(e, \nu)^7\mathrm{Li}$] could bring freshly synthesized Li onto the stellar surface if the convection is rapid enough. However, our observations in late-type secondaries of cataclysmic binaries do not support it (Martín et al., in preparation). We propose an ongoing Li production process linked to the presence of accretion disks and strong

X-ray outbursts, which is an obvious characteristic common to our three systems. During outbursts there is strong particle acceleration as evidenced by nonthermal radio emission (Hjellming et al. 1988). High-energy (MeV) p- and α-particles may also be produced which are capable of spallating He, C, N, O nuclei in the accretion disk or in the companion itself.

Although it is beyond the scope of this paper to make a detailed study of Li production mechanisms in SXTs, it is simple to test if there is enough energy in the outbursts to account for the observed Li abundances. We start from the conservative assumption that the secondary has log $N(\text{Li}) = 3$ throughout (in reality only the outer layers of the star have Li abundance), and a mass of 0.5 $M_\odot$, which gives a total number of $\sim 3 \times 10^{48}$ Li nuclei. The energy required to produce them by spallation reactions is in the range 10^{47}–10^{50} ergs, depending on the plasma temperature of the target nuclei and on the energy of the incident particles. We assumed that such a temperature is between 1–100 keV, easily reached in the inner regions of an accretion disk around a neutron star or a stellar black hole, and used the computations of Canal, Isern, & Sanahuja (1975) and Clayton & Dwek (1976). Taking an outburst with moderate peak X-ray luminosity of order $L_x = 10^{38}$ ergs s^{-1}, lasting for about 1 week, and since at least 10^7 such events can take place during the lifetime of these binaries, we estimate that a total energy of at least 10^{51} ergs is released only in the X-ray domain, an amount of energy comparable to the radiative losses of a pulsar during its lifetime. There seems to be enough energy available during outbursts to produce all the Li nuclei observed in the SXT secondaries by spallation reactions. Following Clayton & Dwek, the energetic requirements would favor α-α reactions as the major source for Li. Jin (1990) claims that α-α collisions are the major reactions for Li production in a model of light element production in the ion pressure–supported accretion torus around a black hole, but his results are not directly applicable to our case because he only considers accretion from the ISM on giant black holes.

In outburst the accretion rate of an SXT can reach the Eddington limit, and a significant fraction of matter may be expelled from the vicinity of the central object. The broad emission lines of SXTs in eruption are thought to originate in disk-driven outflowing material (cf. Blandford 1990). In addition, there is direct evidence for mass loss in the optical spectra of V404 Cyg a few weeks after its X-ray discovery; Casares et al. (1991) reported transient P Cygni profiles in various emission lines, including Hα. Hence, it is likely that the disk loses material via a X-ray–driven wind, which can contaminate the surroundings with fresh Li created near the compact object.

As pointed out in Paper I, α-α reactions would produce excited Be and Li nuclei that decay giving γ-lines at 431 keV and 478 keV. Recently the SIGMA telescope on board the *GRANAT* satellite detected an emission line at 476 ± 15 keV in the SXT Nova Muscae 1991, with a luminosity of about 6×10^{35} ergs s^{-1} (Sunyaev et al. 1992). This feature has been interpreted as a redshifted e^+-e^- annihilation line, but we note the remarkable coincidence of its measured energy with that expected from Li de-excitation. If only 20% of the emission comes from Li synthesis, we estimate that $\sim 5 \times 10^{45}$ Li nuclei would have been produced via α-α reactions during the minimum duration (13 hr) of the event. About 1000 such outbursts would be enough to generate all the Li nuclei that we estimate to be present in the secondaries of our three SXTs. It would clearly be extremely important to observe future γ-emission lines in SXTs at higher resolution, and to search for Li optically in the secondary of Nova Muscae. We note that the same α-α spallations would produce considerable amounts of the ^{6}Li isotope with expected isotopic ratios for these reactions as low as $^7\text{Li}/^6\text{Li} = 5$. The detection of the ^{6}Li isotope would also provide a proof of the spallative scenario.

Finally, we briefly discuss the possible implications of this scenario in a Galactic scale. Assuming the cosmic Li abundance to be $\text{Li/H} = 1 \times 10^{-9}$, i.e., log $N(\text{Li}) = 3$, and taking the mass of the interstellar medium as 10^{10} $M_\odot$, we expect about 10^{58} Li nuclei in the Galactic disk. An energy in the range 10^{57}–10^{60} ergs would be needed for creating such abundance by spallation reactions in SXTs according to the discussion above. The rate of detected X-ray novae events is about 0.5–1 yr^{-1} (Tanaka 1992). The most distant one is at $\sim$3–5 kpc (V404 Cyg), which gives an effective search coverage of the Galactic disk of about 10%. Hence, the current SXT rate in the Galaxy is around 5–10 yr^{-1}. In each outburst the total X-ray energy released is of order 10^{45} ergs. Taking the present rate of SXTs for the last 1 Gyr we infer an energy of 10^{55} ergs, which would only make a negligible contribution to the ISM Li abundance in recent epochs. However, this is consistent with estimates that the cosmic Li abundance has changed little in the last 4.6 Gyr (e.g., Steigman 1993). To establish if spallation reactions around compact objects have significantly contributed to the evolution of Li in the Galactic history, requires detailed modeling. The models should consider not only the low-mass, but also the high-mass, X-ray binaries, such as Cyg X-1, which have a birthrate about 100 times higher (e.g., van den Heuvel 1992).

6. CONCLUSIONS

We have detected the Li I resonance line in the quiescent spectrum of Cen X-4, an SXT containing a neutron star. A high Li abundance has been derived for this system, and we also present Li abundances for the black hole binaries A0620−00 and V404 Cyg. Our LTE abundances range from log $N(\text{Li}) = 3.3$ for Cen X-4 to log $N(\text{Li}) = 2.0$ for A0620−00. Non-LTE corrections change these values to 3.1 and 2.1, respectively.

Given current evolutionary scenarios for SXTs, it is expected that the Li has been substantially depleted in the secondaries by post–main-sequence dilution, mass loss, and convective mixing. A process of Li production seems needed to account for the high Li abundances observed. Several mechanisms are possible in the early life of these binaries. There can be ongoing Li production as well; in particular, we argue that spallation reactions in the vicinity of the compact objects during X-ray outbursts meet the energetic requirements for explaining the observed Li abundances. Empirical evidence of α-α reactions could come from future high-resolution observations of γ-emission features in SXTs, such as that detected in Nova Muscae 1991 at 476 keV, or from detection of the ^{6}Li isotope in the photosphere of an SXT's secondary.

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