LITHIUM PRODUCTION ON A LOW-MASS SECONDARY IN A BLACK HOLE SOFT X-RAY TRANSIENT

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ABSTRACT

We examine production of Li on the surface of a low-mass secondary in a black hole soft X-ray transient (BHSXT) through the spallation of CNO nuclei by neutrons which are ejected from a hot (>10 MeV) advection-dominated accretion flow (ADAF) around the black hole. Using updated binary parameters, cross sections of neutron-induced spallation reactions, and mass accretion rates in ADAFs derived from the spectrum fitting of multiwavelength observations of quiescent BHSXTs, we obtain the equilibrium abundances of Li by equating the production rate of Li and the mass transfer rate through accretion to the black hole. The resulting abundances are found to be in good agreement with the observed values in seven BHSXTs. We note that the abundances vary on a timescale longer than a few months in our model. Moreover, the isotopic ratio $^6\text{Li}/\text{Li}$ is calculated to be about 0.7–0.8 on the secondaries, which is much higher than the ratio measured in meteorites. Detection of such a high value is favorable to the production of Li via spallation and the existence of a hot accretion flow, rather than an accretion disk corona system in quiescent BHSXTs.

Subject headings: accretion, accretion disks — black hole physics — nuclear reactions, nucleosynthesis, abundances — stars: abundances

1. INTRODUCTION

High abundances of Li have been detected in late-type secondaries of black hole soft X-ray transients (BHSXTs) and a neutron star soft X-ray transient (NSSXT) in quiescence (Martin et al. 1992, 1994, 1996), although Li would be destroyed in the deep convective envelope of a late-type star. The Li enrichment has not, however, been observed on a late-type secondary in a compact binary with a white dwarf (Martin et al. 1995). These facts strongly suggest that a production mechanism for Li operates in compact binaries (Yi & Narayan 1997; Guessoum & Kazanas 1999) and that the nature of the primaries is crucial for the mechanism, although rotation might reduce the destruction of Li in the envelope of the secondary (Mac Carrone et al. 2005).

Multimwavelength spectra of BHSXTs in quiescence are successfully fitted to the radiation from an advection-dominated accretion flow (ADAF) around the black hole (Narayan et al. 1995a, 1995b). The density is so low in ADAFs that ions interact inefficiently with electrons. Consequently ions have high temperatures due to viscous heating up to about 30 MeV near the inner edge of ADAF. At such high temperatures, $\alpha-\alpha$ reactions proceed to synthesize Li inside ADAFs (Martin et al. 1994; Yi & Narayan 1997). It is necessary that a fraction $10^{-3}$ to $10^{-4}$ of the accreting gas is transported to the secondary to explain the high abundances of Li observed in BHSXTs. However, such a high fraction is uncertain to be realized due to strong gravity of the black hole and the Coulomb interactions with nuclei inside ADAFs (Guessoum & Kazanas 1999). Helium breaks via spallation with protons to produce neutrons at the inner edge of ADAFs. A large fraction of neutrons can be ejected from ADAFs, because they do not interact with nuclei through the Coulomb interactions. Neutrons intercepted by the secondary interact with CNO nuclei through spallation to produce Li on the surface (Guessoum & Kazanas 1999). This scenario is of particular interest, because the Li enrichment is anticipated in secondaries of BHSXTs and NSSXTs. It does not work, however, in white dwarfs as primaries due to low disk temperature for helium breakup into nucleons.

In the present Letter, we evaluate Li abundances on the surface of secondaries in BHSXTs, following the scenario proposed by Guessoum & Kazanas (1999). To this end, we use updated binary parameters, such as the mass $M$ of a black hole, the mass $M_\ast$ and radius $R_\ast$ of a secondary, mass accretion rates derived from the spectrum fitting of multiwavelength observation of BHSXTs in quiescence, and cross sections of neutron-induced spallation reactions. Then, we compare the resulting abundances with the observed values.

2. NEUTRON PRODUCTION IN AN ADVECTION-DOMINATED ACCRETION FLOW

The temperature of ions in ADAFs is comparable to the virial temperature and is given at radius $r$ by (Narayan & Yi 1994, 1995a, 1995b)

$$T = 3.7 \times 10^{12} \frac{\dot{M}}{\dot{m}_\ast} \text{K} = 31.9 \frac{\dot{M}}{\dot{m}_\ast} \text{MeV}. \quad (1)$$

Here $r_{\text{in}}$ is the radius at the inner edge of the ADAF and is set to be $3r_\ast$, where $r_\ast$ is the Schwarzschild radius of the black hole. The number density is given by

$$n = 1.7 \times 10^{18} \alpha^{-1} m^{-1} \dot{m} \left( \frac{r}{r_{\text{in}}} \right)^{-3/2} \text{cm}^{-3}, \quad (2)$$

where $\alpha$ is the viscous parameter, $m = M/M_\odot$, and $\dot{m}$ is the mass accretion rate in units of the Eddington accretion rate $\dot{M}_{\text{edd}} = 1.4 \times 10^{17} m \text{ g s}^{-1}$.

Once the temperatures, densities, and drift timescales are specified, we can follow the abundance evolution in the ADAF from the outer boundary $r_{\text{out}}$ to $r_{\text{in}}$, using a nuclear reaction network. We set $r_{\text{out}}$ to be $100r_\ast$. It is likely that $r_{\text{out}}$ becomes much larger during the quiescent state (Narayan et al. 1997), but the abundance of neutrons is independent of the choice of
larger $r_{\text{out}}$ because of low temperatures (<1 MeV) in the outer region (Guessoum & Kazanas 1999). Our network contains 17 species of nuclei: $n$, $p$, $D$, $T$, $^3\text{He}$, $^4\text{He}$, $^9\text{B}$, $^{11}\text{C}$, $^{12}\text{C}$, $^{13}\text{N}$, $^{14}\text{N}$, $^{15}\text{O}$, $^{16}\text{O}$, $^{17}\text{F}$, $^{20}\text{Ne}$, $^{21}\text{Na}$, and $^{24}\text{Mg}$, and 14 reactions, whose rates are taken from Table 1 in Guessoum & Gould (1989). It should be emphasized that photodisintegration reactions are not important for abundance evolution inside ADAFs, since ADAFs are optically thin and photons have no chance to interact with nuclei due to low gas densities. Therefore, nuclear statistical equilibrium cannot be realized in ADAFs even for high temperatures. The network is appropriate for the study of the production of neutrons in ADAFs, but insufficient for heavy nuclei as well as Li because of the limited numbers of nuclei and reactions. The initial abundance at $r_{\text{out}}$ is set to be the solar composition (Anders & Grevesse 1989).

Figure 1 shows the abundance distribution inside an ADAF for $\alpha = 0.3$, $m = 10$, and $m = 10^{-3}$. Neutrons are produced significantly via the breakup of $^4\text{He}$ at $r < 20r_g$. The distribution of neutrons is similar to that in Figure 1 of Jean & Guessoum (2001). We note that the number fraction of neutrons $Y_n$ depends not on $m$ solely, but on the combination $m/\alpha$. Hereafter we fix $\alpha = 0.3$ in the present Letter (Narayan et al. 1997). It should be emphasized that the breakup of helium cannot take place in the present Letter (Narayan et al. 1997). It should be emphasized that photodisintegration reactions are not important for abundance evolution inside ADAFs, since ADAFs are optically thin and photons have no chance to interact with nuclei due to low gas densities. Therefore, nuclear statistical equilibrium cannot be realized in ADAFs even for high temperatures. The network is appropriate for the study of the production of neutrons in ADAFs, but insufficient for heavy nuclei as well as Li because of the limited numbers of nuclei and reactions. The initial abundance at $r_{\text{out}}$ is set to be the solar composition (Anders & Grevesse 1989).

The neutrons produced in ADAFs have positive Bernoulli numbers (Narayan & Yi 1994), so that a fraction of the neutrons thermally overcome the deep gravitational well of the black hole before inelastic scattering with protons. The ejection fraction of neutrons from ADAFs as

$$f_{\text{ej}} = \frac{\dot{\nu}}{\dot{\nu}_{\text{in}}}$$

in an accretion corona, which is an alternative scenario to explain the multiwavelength spectrum of BHsXe (e.g., Malzac 2007) because of low ion temperatures comparable to electron temperature (<1 MeV).

The neutrons produced in ADAFs have positive Bernoulli numbers (Narayan & Yi 1994), so that a fraction of the neutrons thermally overcome the deep gravitational well of the black hole before inelastic scattering with protons. The ejection fraction of neutrons from ADAFs is evaluated from equation (14) in Guessoum & Kazanas (1990) using the pseudo-Newtonian potential and an experimentally measured cross section of the neutron-proton inelastic scattering, $\sigma_{np} = 671.0(14.1\text{ MeV}/E_n)$ mbarn (Tanaka et al. 1970), where $E_n$ is the energy of neutrons. The distribution function of neutrons is set to be Maxwellian with ion temperatures of ADAFs (Guessoum & Kazanas 1990, 1999). We find that $f_{\text{ej}} = 0.12$, which depends weakly on $r$ as seen from Figure 1. We note that $f_{\text{ej}}$ is independent of $\alpha$, $m$, and $m$.

Using the mass conservation in ADAFs, we evaluate the ejection rate of neutrons from ADAFs as

$$\dot{N}_n = \int_{r_{\text{in}}}^{r_{\text{out}}} f_{\text{ej}} \frac{dY}{dt} m_{n} d\tau = \frac{M}{m_{n}} \int_{r_{\text{in}}}^{r_{\text{out}}} Y_{n,\text{in}} f_{\text{ej},\text{in}} d\tau$$

$$\approx 1.1 \times 10^{-14} \left( \frac{m}{10^3} \right) \left( \frac{m_{n}}{10} \right) \left( \frac{f_{\text{ej},\text{in}}}{0.1} \right) \left( \frac{Y_{n,\text{in}}}{10^{-2}} \right) \text{ s}^{-1},$$

where $\Sigma$ is the surface density in ADAFs, and $f_{\text{ej},\text{in}}$ and $Y_{n,\text{in}}$ are the values of $f_{\text{ej}}$ and $Y_n$ at $r_{\text{in}}$. Here we have used a relation $d\tau/d\tau = 0$ (see Fig. 1). We note that the rate is unlikely to change significantly for smaller $r_{\text{in}}$. Even if we set $r_{\text{in}} < 3r_g$, the increase in $Y_{n,\text{in}}$ due to higher temperatures would be canceled out by a large decrease in $f_{\text{ej},\text{in}}$, resulting from general relativistic effects.

Next we calculate the energy of the ejected neutrons averaged over the region from $r_{\text{in}}$ to $r_{\text{out}}$ as

$$\langle E_{\text{ej}} \rangle = \frac{1}{\dot{N}_n} \int_{r_{\text{in}}}^{r_{\text{out}}} E_{\text{ej}} f_{\text{ej}} \frac{dY}{dt} 2\pi r \Sigma d\tau,$$

where $E_{\text{ej}}$ is the energy of ejected neutrons, and is evaluated the same way as in $f_{\text{ej}}$. We note that $\langle E_{\text{ej}} \rangle$ is crucial for the production of Li on the secondary, because cross sections of both the spallation reactions and the inelastic scattering with protons depend strongly on the neutron energy. We find that $\langle E_{\text{ej}} \rangle = 78$ MeV, which is insensitive to $\alpha$, $m$, and $m$.

3. Li Production on the Secondary through Spallation of CNO Nuclei by Neutrons

The surface of the secondary in BHsXes is bombarded by neutrons from the ADAF. We note that $\beta$-decays of neutrons can be ignored, because their half-life is much longer than the elapsed time $230(aR_*/v_\gamma) (0.1/v_\gamma)$ s during the flight from the ADAF to the surface, where $a$ and $v_\gamma$ are the binary separation and the ejection velocity in units of the velocity of light. The depth of the envelope exposed by neutrons is expressed as $1/n_p$, where $n_p$ is the number density of protons on the surface of the secondary, since the neutron-proton inelastic scattering is predominant. The mass of the neutron-exposed envelope is given by

$$M_{\text{exp}} = 2.3 \times 10^{-10} \left( \frac{R_*}{0.7 R_\odot} \right)^2 \left( \frac{0.9}{Y_p} \right) \left( \frac{121 \text{ mbar}}{\sigma_{np}} \right) M_\odot.$$

The abundance of Li increases through the spallation of CNO nuclei by neutrons on the secondary. For the isotropic ejection of neutrons from ADAFs, the production rate of Li is given by

$$\dot{M}_{\text{Li}} \approx \frac{1}{24 \pi a^2} \sigma_{np} M_{\text{exp}} Y_{\text{CNO}} A_{\text{Li}}$$

$$\approx 1.6 \times 10^{-20} \left( \frac{m}{10} \right) \left( \frac{m_{n}}{10} \right) \left( \frac{f_{\text{ej},\text{in}}}{0.1} \right) \left( \frac{Y_{n,\text{in}}}{10^{-2}} \right) \left( \frac{\sigma_{np}}{25 \text{ mbar}} \right) \times \left( \frac{121 \text{ mbar}}{\sigma_{np}} \right) \left( \frac{R_*}{0.25a} \right)^2 \text{ mbar} \text{ yr}^{-1},$$

where $A_{\text{Li}}$ is the average mass number of Li, which is composed
of $^6$Li and $^7$Li, and is set to be 7; $\sigma_{sp}$ is the total cross section of the spallation reactions of CNO nuclei, and $Y_{CNO}$ is the number fraction of CNO nuclei, which is $1.2 \times 10^{-3}$ for the solar abundances (Anders & Grevesse 1989). The factor 1/2 in equation (6) means that half of the surface of the secondary is exposed to neutrons from the ADAF.

On the other hand, a fraction of the produced Li is transported to the black hole through accretion. The mass transfer rate of Li from the envelope is expressed as

$$M_{Li} = 1.5 \times 10^{-20} \left( \frac{Y_{Li}}{10^{-10}} \right) \left( \frac{m}{10} \right) \left( \frac{\dot{m}}{10^{-3}} \right) M_\odot \text{ yr}^{-1}. \tag{7}$$

It should be noted that the destruction rate of Li in the envelope is $7M_{exp}Y_{Li}/f_{dep}$, which is much smaller than $M_{Li}$ even for a short destruction timescale $t_{dep} = 10^7$ yr. Moreover, we emphasize that the Li depletion due to convective matter mixing can be ignored in the neutron-exposed envelope. This is because almost all the envelope is included in a photosphere of secondaries, so that the convective mixing is not significantly important in the envelope (Ludwig et al. 2006). In fact, the masses of the photosphere are $9.0 \times 10^{-11}$ and $4.6 \times 10^{-11} M_\odot$ for secondaries of 0.7 and 0.2 M_\odot at $10^{10}$ yr from their birth, respectively (Siess et al. 2000), and are comparable to $M_{exp}$ (eq. [5]). Here we have evaluated the photosphere masses as those in surface layers of optical depth from 0.005 to 1. On a timescale of the Li enhancement (eq. [9]), only a tiny fraction of the enhanced Li in the envelope is likely to diffuse into deeper convective layers to deplete Li in the hot convective envelope of the secondaries through nuclear burning. For equilibrium between the production and loss rates $M_{Li} = M_{Li}$, one can obtain

$$\dot{Y}_{Li, eq} \approx 1.1 \times 10^{-10} \left( \frac{f_{Li, in}}{0.1} \right) \left( \frac{Y_{Zn, eq}}{10^{-10}} \right) \left( \frac{0.9}{Y_p} \right) \left( \frac{Y_{CNO}}{10^{-3}} \right) \times \left( \frac{\sigma_{sp}}{25 \text{ m barn}} \right) \left( \frac{212 \text{ m barn}}{\sigma_{sp}} \right) \left( \frac{R_*}{0.25 a} \right)^2. \tag{8}$$

It should be emphasized that $\dot{Y}_{Li, eq}$ depends on $\alpha$ and $\dot{m}$ as the combination of $m/\alpha^2$ through $\dot{Y}_{Li, eq}$.

The timescale for the Li enhancement is given by

$$\tau_{eq} = M_{exp} \dot{Y}_{Li, eq}/M_{Li} \approx 10.2 \left( \frac{f_{Li, in}}{0.1} \right)^{-1} \left( \frac{Y_{Zn, eq}}{10^{-10}} \right)^{-1} \left( \frac{Y_{Zn, eq}}{10^{-10}} \right) \left( \frac{0.9}{Y_p} \right) \left( \frac{Y_{CNO}}{10^{-3}} \right)^{-1} \times \left( \frac{\sigma_{sp}}{25 \text{ m barn}} \right) \left( \frac{212 \text{ m barn}}{\sigma_{sp}} \right) \left( \frac{R_*}{0.25 a} \right)^2 \text{ yr.} \tag{9}$$

Therefore, it takes a few years for lithium to achieve the equilibrium abundance of $10^{-10}$. We note that the Li abundance varies on a timescale longer than a few months in our model, while this is not the case in the scenario proposed by Yi & Narayan (1997).

Finally, we evaluate the total cross sections of spallation reactions of CNO nuclei induced by neutrons as the sum of the cross sections of $^{12}$C, $^{14}$N, and $^{16}$O weighted by their number fractions. The cross sections for $^{12}$C, $^{14}$N, and $^{16}$O are calculated from the Taly nucleus reaction code (Koning et al. 2005). The energy distribution of neutrons just before the spallation is assumed to be the same as that of neutrons ejected from the ADAF, because neutrons are unlikely to lose their energies largely during the flight. For the solar abundance and $E_n = \langle E_n \rangle = 78$ MeV, we find that the cross sections are $\sigma_{sp} = 0.5$ m barn and $\sigma_{sp} = 15.3$ m barn for the production of $^6$Li and $^7$Li, respectively, yielding the sum $\sigma_{sp} = \sigma_{sp} + \sigma_{sp} = 25.8$ m barn. If we adopt the abundance of CNO-processed material, in which all the original $^{12}$C are converted to $^{14}$N through CNO cycle in the interior of the secondary, the total cross section decreases to $\sigma_{sp} = 18.0$ m barn.

4. COMPARISON WITH OBSERVATIONS

We compare the evaluated and observed abundances of Li in seven BHSXTs, using updated parameters of the binaries in Table 1. The radii of the secondaries are taken from the simulations of the evolution of (single) spherical stars with corresponding masses and the solar metallicity at 1 Gyr (Table 2 in Chabrier & Baraffe 1997); they vary from 0.21 to 0.67 $R_\odot$ as the secondary masses increase. The binary separations are calculated from $R_*/a = 0.46(1 + M/M_p)^{-0.5}$ (Paczynski 1971). The observed abundances of Li are adopted from Casares et al. (2007). We note that an upper limit of $A(Li)_{obs}$ for GRO 0422+32 was evaluated as a higher value (2.0; Martin et al. 1996), instead of 1.62 (Casares et al. 2007), which has been obtained from the realanalysis of observational data by Martin et al. (1996).

The mass accretion rates in ADAFs are found from the spectrum fitting of multiwavelength observations of quiescent BHSXTs to be $m_{spa} = 4.3 \times 10^{-3}$ and $2.0 \times 10^{-2}$ for A0620-003 and V404 Cyg, respectively (Narayan et al. 1997; Quataert & Narayan 1999). For the other objects, where the spectrum fitting has not yet been performed in quiescence, we simply specify the accretion rates from the minimum X-ray luminosities in these systems (Garcia et al. 2001; McClintock et al. 2003). These values of $m_{spa}$ are given in Table 2.

Using these values of parameters all together, we can calculate the equilibrium abundances of Li on the secondaries in seven BHSXTs. The resulting abundances $A(Li) = \log \left( Y_{Li, eq}/Y_p \right) + 12$ are adopted from Table 5 in Casares et al. (2007).

Bradley et al. (2007).

Froning et al. (2007).

Esin et al. (1998) and references therein.
12 and the enhancement timescale $t_{\text{en}}$ are given in Table 2. We show $A(\text{Li})$ against the orbital periods $P_{\text{orb}}$ of the binaries by the open circles in Figure 2. We find that our results are in good agreement with the observed abundances, in particular for $P_{\text{orb}} \geq 0.3$ days. The difference in the Li abundances on secondaries is possibly due to their different mass accretion rates, rather than a difference in the operation of Li depletion via hot-bottom burning (Casares et al. 2007). If we adopt the composition of CNO-processed material for the secondary, we obtain lower abundances of Li, as denoted by the open squares in Figure 2. This is favorable to BHSXTs with $P_{\text{orb}} < 0.3$ days, such as XTE J1118+480 (Ergma & Sarna 2001; Haswell et al. 2002).

Next, we try to fit our results to the observed Li abundances with varying accretion rates. The resulting best-fit rates $\dot{m}_{\text{acc}}$ are given in Table 2. We find that they are comparable to or slightly lower than $\dot{m}_{\text{acc}}$. They are also nearly 1/3 of the rates $\dot{m}_{\text{r}}$ predicted by binary evolution models (King et al. 1996), where the factor 1/3 is accounted for by the accumulation of accreting material on the outer thin disk (Menou et al. 1999).

Finally, we evaluate the isotopic ratio $^{67}\text{Li}/^{67}\text{Li}$ on the secondaries. It is easily calculated from the cross sections of $^{6}\text{Li}$ and $^{7}\text{Li}$ for the spallation reactions, or $\sigma_{\text{spall}}/\sigma_{\text{cf}}$, to be $0.69 - 0.81$, depending on the CNO abundances of the secondaries for $E_{\gamma} = 78$ MeV. We note that the ratio is much larger than 0.12 for NSSXT Cen X-4 (Casares et al. 2007) and 0.081 for meteorites (Anders & Grevesse 1989). Detection of such a high $^{67}\text{Li}/^{67}\text{Li}$ ratio will be evidence for the production of Li on the secondaries in BH SXTs and for the existence of an ADAF, rather than an accretion disk corona system (e.g., Malzac 2007), although measurements of the ratio are difficult even for bright solar-type stars (Cayrel et al. 2007).

In the present Letter, we have concentrated on the case of BH SXTs. The spallation of CNO nuclei on secondaries via neutrons is insufficient for the high Li abundances observed on secondaries of NSSXTs, such as Cen X-4, because of low mass accretion rates (Asai et al. 1996). Lithium is likely to be enhanced via the transportation from ADAFs to the secondaries due to the propeller effect. We will examine the Li abundances on the secondaries of NSSXTs based on such a scenario in a future study. We will also evaluate the abundances of Be and B produced via neutron-induced spallation and $\gamma$-ray lines emitted through neutron capture on the secondary. This is our future task.

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