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Lithium Production in Hot Advection-Dominated Accretion Flows in Soft X-Ray Transients

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ABSTRACT

High Li abundances have been reported in the late type secondaries of five soft X-ray transients (SXTs), V404 Cyg, A0620-00, GS2000+25, Nova Mus 1991, and Cen X-4. Since Li is likely to be depleted in stars of this type, the origin of the Li is puzzling. Li has not been seen in similar secondaries of cataclysmic variables, which suggests that the high Li abundance is not due to an anomalous suppression of Li depletion in close binaries. SXTs in the quiescent state have hot advection-dominated accretion flows (ADAFs) in which the ions are essentially at virial temperature. At such temperatures, Li production via $\alpha - \alpha$ spallation is possible. We show that quiescent SXTs can produce sufficient Li via spallation to explain the observations in V404 Cyg, A0620-00, GS2000+25, and Nova Mus 1991. Depending on the Li depletion time scale in the secondary, which may range between $10^7 - 10^9$ yr, the model requires $\sim 10^{-4} - 10^{-6}$ of the accreted mass to be intercepted by the secondary after undergoing Li production and being ejected. In the case of Cen X-4, we can explain the observed Li only if the mass accretion rate is $\sim 10^{-3}$ times the Eddington rate and if there is enhanced ejection due to a propeller effect. We discuss possible observational tests of this proposal. Li production during outbursts could be quite important and may even dominate over the production during quiescence, but the estimate of the Li yield is uncertain. We calculate the expected luminosity in gamma-ray lines due to the production of excited Li and Be nuclei, but conclude that the line cannot be detected with current instruments.

Subject headings: accretion, accretion disks – black hole physics – stars: abundances – stars: neutron – X-ray binaries

1. Introduction

Recently, Martin et al. (1992b, 1994a, 1996) detected Li in the late K-type secondaries of four soft X-ray transients (SXTs), V404 Cyg, A0620-00, Cen X-4, and Nova Mus 1991, while Filippenko

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et al. (1995) and Harlaftis et al. (1996) detected Li in a fifth SXT, GS2000+25. These detections are surprising because late K-type stars do not usually have strong Li features (Brown et al. 1989, Pallavicini et al. 1992). Lithium is destroyed in stellar interiors, and the Li in the surface layers of these stars is expected to be depleted through mixing, diffusion, or post-main sequence dilution (Martin et al. 1994ab and references therein). The high abundances seen in SXTs imply that either there is some Li production mechanism in these systems or that Li depletion is strongly suppressed in their secondaries. Martin et al. (1995) found that cataclysmic variables (CVs) with late type secondary stars similar to those in SXTs do not show Li. This strongly suggests that suppression of Li depletion in the secondaries is not a viable explanation. One must, therefore, take seriously the possibility that the accretion flows in SXTs produce Li. Moreover, one must identify a mechanism which works in the case of accreting black holes and neutron stars, but not for accreting white dwarfs.

Accretion flows around black holes at low mass accretion rates have been successfully modeled as hot advection-dominated accretion flows (ADAFs) in which most of the viscously dissipated energy is retained within the flow and carried inward rather than being lost through radiative cooling (Narayan & Yi 1994, 1995b, Abramowicz et al. 1995, Chen et al. 1995). The ADAF model has been applied to A0620-00 and V404 Cyg in their quiescent state (Narayan, McClintock, & Yi 1996, Narayan, Barret, & McClintock 1997). These studies provide a convincing explanation of the observed X-ray and optical spectra and constrain the parameters of the accretion flow, including the mass accretion rate and the temperature and density of the gas.

In the ADAF model, the ions remain essentially virialized at all radii, with proton temperatures approaching $\sim 10^{12} K$ near the central black hole or neutron star (Rees et al. 1982, Narayan & Yi 1995b). As a consequence, nuclei with energies > 10 MeV per nucleon are abundant and spallation processes become possible (Ramadurai & Rees 1985, Jin 1990, Martin et al. 1994ab). Ramadurai & Rees (1985) considered “ion tori” around pregalactic massive Pop III remnants and examined deuterium production and its implication for big bang nucleosynthesis. Jin (1990) studied the production of ^7Li and other light nuclei in ion tori and derived constraints on the light element enrichment of the Galaxy. Martin et al. (1992, 1994ab) argued that the observed high Li abundances seen in SXTs could be explained by spallation among energetic particles during outbursts of SXTs.

In this paper, we quantitatively examine Li production through spallation in ADAFs and show that SXTs in quiescence are quite efficient at producing Li. The Li yield which we calculate is more than adequate to explain the observed abundances in the black hole SXTs, V404 Cyg, A0620-00, Nova Mus 1991 and GS2000+25, while in the case of the neutron star SXT, Cen X-4, we need to invoke some assistance from a propeller mechanism.

2. Hot Advection Dominated Flows and Lithium Production

2.1. $\alpha - \alpha$ Spallation Cross-Section

The relevant Li production process in hot ADAFs is $\alpha - \alpha$ spallation, ${}^4\text{He}(\alpha, p){}^7\text{Li}$, while Li destruction occurs primarily through the proton initiated process, ${}^7\text{Li}(p, \alpha){}^4\text{He}$ (Rytler 1970, Meneguzzi et al. 1971, Bodansky et al. 1975, Jin 1990). The symbols p , α refer to H, ${}^4\text{He}$ respectively. For particles with energies much higher than those achieved in ADAFs, Li production is possible in spallation processes involving heavier elements such as C, N, O (Meneguzzi et al. 1971, Meneguzzi & Reeves 1975, Reeves 1974, Boesgaard & Steigman 1985, Jin 1990), but this channel is not of interest in ADAFs. The ratio of the production and destruction rates of Li via $\alpha - \alpha$ spallation is given by $n_\alpha n_\alpha v_{\alpha\alpha} \sigma_+ / n_p n_{\text{Li}} v_{p\text{Li}} \sigma_-$, where the n 's refer to particle number densities, the v 's are relative particle speeds, and $\sigma_+(-)$ are the production (destruction) cross-sections. Since we generally have $n_\alpha \gg n_{\text{Li}}$, the effect of destruction is negligible whenever the production cross-section is non-vanishing; destruction becomes dominant only when production ceases altogether, which requires the mean particle energy to be less than a few MeV per nucleon (e.g. Reeves 1974).

The Li production cross-section through $\alpha - \alpha$ spallation is essentially zero for $E < 8.5$ MeV, where E is the mean relative kinetic energy per nucleon (i.e. the energy per nucleon of one of the particles as viewed in the rest frame of the other particle). Above this energy, the cross-section increases rapidly, reaching a value ~ 100 mb at $E \sim 9$ MeV. The cross-section decreases again rapidly for $E > 15$ MeV, falling to a few mb at $E \sim 40$ MeV (Meneguzzi et al. 1971, Bodansky et al. 1975, Jin 1990, and references therein). For simplicity, we model the cross-section as

$$\sigma_+(E) \approx 100(E/10 \text{ MeV})^{-2} \text{ mb}, \quad E \geq 8.5 \text{ MeV}. \quad (2-1)$$

This is the total cross-section for the production of ${}^7\text{Li}$ in its ground state and excited state (at 478 keV) as well as the production of ${}^7\text{Be}$, via ${}^4\text{He}(\alpha, n){}^7\text{Be}$, in its ground state and excited state (at 431 keV); ${}^7\text{Be}$ decays into ${}^7\text{Li}$ through electron capture and is an important channel for Li production (Meneguzzi et al. 1971, Bodansky et al. 1975). The cross-sections for the four species, ${}^7\text{Li}$, ${}^7\text{Li}^*$, ${}^7\text{Be}$, and ${}^7\text{Be}^*$ (where the $*$'s represent excited nuclei) are roughly equal (Burcham et al. 1958, Kozlovsky & Ramaty 1974, Bodansky et al. 1975 and references therein).

2.2. Advection-Dominated Accretion Flows

The dynamical properties of ADAFs are well understood, and detailed global solutions as a function of radius, with physically motivated boundary conditions, have been calculated (Narayan, Kato & Honma 1997, Chen, Abramowicz & Lasota 1997). For many purposes, however, it is sufficient to make use of a simpler self-similar solution obtained by Narayan & Yi (1994, 1995b, see also Spruit et al. 1987). According to this solution, the density, proton temperature, and radial velocity have the following dependences as a function of the dimensionless radius r in

Schwarzschild units ($r \equiv R/R_S$, $R_S = 2GM/c^2$, $M =$ mass of the accreting star),

$$\rho = 3.79 \times 10^{-5} \alpha^{-1} c_1^{-1} c_3^{-1/2} m^{-1} \dot{m} r^{-3/2}, \quad (2-2)$$

$$T = 6.66 \times 10^{12} \beta c_3 r^{-1} \text{ K}, \quad (2-3)$$

$$v_R = 2.12 \times 10^{10} \alpha c_1 r^{-1/2} \text{ cm s}^{-1}. \quad (2-4)$$

Here $m = M/M_\odot$ is the mass of the star in solar units, $\dot{m} = \dot{M}/\dot{M}_{Edd} = \dot{M}/1.39 \times 10^{18} m \text{ g s}^{-1}$ is the mass accretion rate in Eddington units, and α is the usual viscosity parameter (e.g. Frank et al. 1992); β is the ratio of gas pressure to total pressure, and the constants c_1 and c_3 are defined in Narayan & Yi (1995b). (Note that the formula for the ratio of specific heats γ given in equation 2.7 of Narayan & Yi 1995b should be replaced by $\gamma = (8 - 3\beta)/(6 - 3\beta)$, as shown by Esin 1996).

In the following we retain α as a free parameter, assigning a value $\alpha = 0.3$ whenever we need numerical estimates. We assume that $\beta = 0.5$, corresponding to gas and magnetic pressure in equipartition. For this choice of β , we have $c_1 = 1/2$, $c_3 = 1/3$. Assuming that the accreting gas consists of 75% H and 25% He by mass, the number densities of H and ^4He nuclei are given by

$$n_H = 5.93 \times 10^{19} \alpha^{-1} m^{-1} \dot{m} r^{-3/2} \text{ cm}^{-3}, \quad (2-5)$$

$$n_\alpha = 4.94 \times 10^{18} \alpha^{-1} m^{-1} \dot{m} r^{-3/2} \text{ cm}^{-3}. \quad (2-6)$$

We assume that the heating rates of different particles in the gas are proportional to their individual masses, as often assumed for modeling viscous heating in hot accretion flows (Shapiro, Lightman & Eardley 1976, Rees et al. 1982). This assumption (or something similar to it) is critical for the viability of two-temperature ADAF models. Under it, most of the viscous energy goes into the ions, and very little goes to the electrons. If in addition ion-electron coupling via Coulomb collisions is inefficient, then the electrons decouple from the ions and cool radiatively to a much lower temperature than the ions. This leads to a radiatively inefficient two-temperature ADAF.

Energy transfer among ions via Coulomb collisions is even more inefficient than ion-electron energy transfer. Therefore, if the various species of ions receive different amounts of energy through heating, they will not come into thermodynamic equilibrium with one another. In fact, it is unlikely that the individual ion species will achieve a thermal energy distribution among themselves. Therefore, when we discuss below the “temperature” of ions, we refer merely to the mean energy of the particles.

If the heating rate is proportional to particle mass as assumed above, the mean energy *per nucleon* of the various nuclear species will be the same, namely $3kT/2$. We assume this in what follows. (However, as a practical matter, it makes little difference for this paper whether different nuclei have the same temperature or the same energy per nucleon; we choose the latter merely because it seems more natural under the assumptions underlying the ADAF paradigm.) If we

consider two interacting particles in the rest frame of one of the particles, the mean energy per nucleon of the other particle is $3kT$ and the rms relative speed is $v_r = \sqrt{6kT/m_u}$:

$$E = 287r^{-1/2} \text{ MeV}, \quad (2-7)$$

$$v_r = 2.35 \times 10^{10} r^{-1/2} \text{ cm s}^{-1}. \quad (2-8)$$

2.3. Lithium Production in ADAFs

For simplicity, we assume here that all pairs of interacting particles have the same relative energy E and relative velocity v_r as given in equations (2-7) and (2-8). Section 3.3 discusses a more detailed calculation where we use the full particle energy distribution.

The abundance of Li grows as a result of spallation as the accreting gas flows in. The change in the abundance over a radial distance ΔR is given by

$$\frac{\Delta n_{Li}}{n_H} = \frac{1}{2} \sigma_+(E) v_r \frac{n_\alpha^2}{n_H} \Delta t_{flow}, \quad (2-9)$$

where $\Delta t_{flow} = \Delta R/v_r$. The factor $1/2$ is to correct for double counting of α particles. Since $\sigma_+ \propto E^{-2} \propto T^{-2} \propto r^2$ and $\Delta t_{flow} = -(R/v_R) \Delta \ln R \sim -r^{3/2} \Delta \ln r$, we have $\Delta n_{Li}/n_H \propto -r^{3/2} \Delta \ln r$. Thus, most of the Li is produced at larger radii. The production switches on suddenly when E crosses 8.5 MeV at $r_{out} = 33.8$, and the rate of production then decreases as the gas flows in. This feature means that it is legitimate to use the self-similar equations (2-2)–(2-4), since the exact global solutions are very close to the self-similar form at large radii and show significant deviations only close to the black hole (Narayan et al. 1997, Chen et al. 1997). Integrating equation (2-9) over radius, the total ${}^7\text{Li}$ abundance in the accreting gas as it approaches the black hole is

$$\frac{n_{Li}}{n_H} = \int d \left(\frac{n_{Li}}{n_H} \right) = \frac{1}{2} \int_1^{r_{out}} \sigma_+ v_r \frac{n_\alpha^2}{n_H} \frac{R_S dr}{v_R} = 2.13 \times 10^{-3} \frac{\dot{m}}{\alpha^2}. \quad (2-10)$$

In terms of mass, the rate of production of Li is

$$\dot{M}_{Li} = 7 \frac{n_{Li}}{n_H} 0.75 \dot{M} = 1.12 \times 10^{-2} \frac{\dot{m}}{\alpha^2} \dot{M} = 2.47 \times 10^{-10} \frac{m \dot{m}^2}{\alpha^2} M_\odot \text{ yr}^{-1}, \quad (2-11)$$

where the factor of 7 is for the number of nucleons per ${}^7\text{Li}$ nucleus, and 0.75 is to allow for the fact that only 0.75 of the accreted mass is in the form of H.

2.4. Lithium Enrichment of the Secondary

We assume that a fraction of the accreting mass is ejected outward in an outflow or wind. This is not unreasonable as ADAFs have been shown to be susceptible to outflows/winds (Narayan

& Yi 1994, 1995a), and there exists direct evidence for ejections in some X-ray binaries (e.g. Hjellming & Han 1995, Foster et al. 1996, and references therein). We further assume that a fraction of the outflowing material is intercepted by the secondary. Thus, we write the fraction of the accreting mass that reaches the secondary as $F_{esc}\Omega$, where Ω is the solid angle of the secondary as viewed from the accreting star. We treat F_{esc} as a parameter, and note that there is considerable uncertainty in its value.

There is at present no reliable physical description of outflows/winds from accreting black holes. Therefore, the total fraction of the accreting mass which flows out is not known. Further, the angular distribution of the outgoing mass is uncertain and it is not clear how much of this mass flows in the direction of the secondary. Finally, the capture probability on the secondary is also uncertain since it could be modified by a stellar wind or a stellar magnetosphere. We take the point of view that any value of $F_{esc} \ll 1$ is “reasonable,” while a value of $F_{esc} \rightarrow 1$ is too optimistic (except in the propeller case considered in §3.3).

The rate at which Li is deposited on the surface of the secondary is given by

$$\dot{M}_{Li,+} = F_{esc}\Omega\dot{M}_{Li} = 2.47 \times 10^{-12} \frac{m\dot{m}^2}{\alpha^2} F_{esc}\Omega_{-2} M_{\odot}\text{yr}^{-1}, \quad (2-12)$$

where $\Omega_{-2} = \Omega/10^{-2}$. In writing this result we assume that most of the outflow occurs from small radii, inside the radius ~ 30 where the bulk of the Li synthesis takes place.

The Li deposited on the secondary is depleted by destruction processes in the star. The depletion time scale is somewhat poorly determined for stars of various kinds (e.g. Boesgaard & Steigman 1985). The original Pop I Li abundance of $\sim 10^{-9}$ (Boesgaard & Steigman 1985, Reeves et al. 1990) with which a star begins its life decreases during several stages of stellar evolution. (i) During the pre-main sequence phase, vigorous convective transport could substantially deplete the surface Li. In young stellar clusters, the depletion is observed to depend on stellar type and there is a significant spread of the abundance from very low values all the way to the primordial value. The depletion time scale appears to be $\sim 10^7 - 10^8$ yr (Martin et al. 1992ab and references therein). (ii) During the main sequence phase of K dwarfs, the depletion time scale appears to be as short as a few $\times 10^8$ yr (e.g. Boesgaard & Steigman 1985, Thorburn et al. 1994, Garcia-Lopez et al. 1994), as suggested by low observed Li abundances (Brown 1989, Pallavicini et al. 1992, Martin et al. 1994b). However, the main sequence depletion time scale for F and G type dwarfs and subgiants may be as long as $\sim 10^9$ yr (e.g. Duncan 1981). (iii) G and K giants appear to deplete Li by a large factor $\sim 10^3$ on a time scale $\sim 5 \times 10^7$ yr (Pilachowski et al. 1984, Boesgaard & Steigman 1985). The depletion time scale of evolved stars such as stripped giants in V404 Cyg and Cen X-4 is poorly known.

We take the depletion time scale to be another free parameter, with a value in the range $10^7 - 10^9$ yr, and we scale our results to a fiducial time scale of 10^8 yr. If the depletion time scale is as long as $\sim 10^9$ yr as suggested by the work of Pinsonneault et al. (1992), then our estimates may be considered conservative.

Let $(n_{Li}/n_H)_{-9}$ be the Li abundance in the envelope of the secondary in units of 10^{-9} . The rate of destruction of Li is given by

$$\dot{M}_{Li,-} = 7 \times 10^{-9} \left(\frac{n_{Li}}{n_H} \right)_{-9} \frac{0.75 M_{env}}{t_D} = 5.25 \times 10^{-18} \frac{M_{env,-1}}{t_{D8}} \left(\frac{n_{Li}}{n_H} \right)_{-9} M_{\odot} \text{yr}^{-1}, \quad (2-13)$$

where $M_{env,-1}$ is the mass of the secondary's envelope in units of $0.1 M_{\odot}$, and t_{D8} is the depletion time in units of 10^8yr . It is likely that in some of our systems the envelope mass is much lower than $0.1 M_{\odot}$ (cf. Pinsonneault et al. 1992). We thus err again on the side of being conservative in our choice of scaling for M_{env} .

If the Li abundance in the secondary has reached a steady state, the enrichment and depletion rates should be equal. Equating (2-12) and (2-13), we then obtain the escape fraction F_{esc} needed in order to explain the observed Li abundance,

$$F_{esc} = 2.13 \times 10^{-6} \frac{\alpha^2}{\dot{m} \dot{m}^2} \frac{M_{env,-1}}{\Omega_{-2} t_{D8}} \left(\frac{n_{Li}}{n_H} \right)_{-9}. \quad (2-14)$$

If the total duration of the accretion flow is shorter than the depletion time of the secondary, then we can neglect Li destruction and assume that the secondary retains all the Li deposited on it during the life of the system as an X-ray binary. In this case, equation (2-14) is replaced by

$$F_{esc} = 4.71 \times 10^{-5} \frac{\alpha^2}{\dot{m}} \frac{M_{env,-1}}{\Omega_{-2} \Delta M_{-1}} \left(\frac{n_{Li}}{n_H} \right)_{-9}, \quad (2-15)$$

where ΔM_{-1} is the total mass transferred from the secondary to the primary in units of $0.1 M_{\odot}$. (We have made use of the relation $\dot{M} = 2.21 \times 10^{-8} \dot{m} M_{\odot} \text{yr}^{-1}$.)

2.5. Gamma-Ray Line Emission

Roughly half the ${}^7\text{Li}$ and ${}^7\text{Be}$ nuclei produced via $\alpha - \alpha$ spallation are in an excited state. When these nuclei make a transition to the ground state they emit gamma-rays at 478 keV (${}^7\text{Li}^*$) and 431 keV (${}^7\text{Be}^*$) respectively (Kozlovsky & Ramaty 1974). If this line emission could be detected it would provide strong support for the spallation scenario (Martin et al. 1992b, 1994b). Using the Li production rate estimated in section 2.3, we calculate the luminosity in gamma-ray lines to be

$$L_{\gamma} \sim 4.86 \times 10^{32} \frac{\dot{m} \dot{m}^2}{\alpha^2} \text{erg s}^{-1}, \quad (2-16)$$

where we have assumed that one quarter of the produced nuclei emit 478 keV photons and one quarter emit 431 keV photons. This is a very low gamma-ray luminosity, especially considering the fact that the ADAF solution is valid only for low mass accretion rates, $\dot{m} < (0.3 - 1) \alpha^2$ (Narayan & Yi 1995b). Setting $\dot{m} = \alpha^2$ and taking $\alpha = 0.3$, we obtain a maximum gamma-ray luminosity of

$$L_{\gamma, \max} = 4.37 \times 10^{31} \dot{m} \text{erg s}^{-1}. \quad (2-17)$$

Even with $m \sim 20$, the maximum likely mass of a black hole in an X-ray binary, the luminosity is too low to be detected with current detectors. Furthermore, the time scale for gamma-ray emission from excited nuclei, of the order of days to weeks, is fairly long (mainly determined by the electron capture time scale for ${}^7\text{Be}$ nuclei; cf. Browne & Firestone 1986) and so most of the nuclei are likely to disappear into the black hole before they can decay and emit gamma-rays. (This is not an issue for neutron star SXTs.) The line may possibly be within the limits of the SPI Ge spectrometer on the INTEGRAL mission.

When $\dot{m} > \alpha^2$, the accretion flow is likely to be in the form of a cool geometrically thin accretion disk (e.g. Frank et al. 1992). In such disks, spallation can occur (if at all) only in non-thermal flares (e.g. Field & Rogers 1993). If flare activity is large enough and if it produces high energy alpha particles (> 10 MeV per nucleon) in a dense environment, then in principle one might have a detectable flux of gamma-ray lines. But such a model does not fall within the scope of the ADAF paradigm considered here.

3. Application to Soft X-Ray Transient Systems

In this section we apply the above estimates to the SXT systems with high observed Li abundances. The solid angles of the secondaries are given by $\Omega = \pi R_{sec}^2 / 4\pi a^2$, where R_{sec} is the radius of the secondary and a is the separation of the two stars. We estimate R_{sec}/a using the fitting formula of Eggleton (1983),

$$\frac{R_{sec}}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}, \quad (3-1)$$

where $q = M_{sec}/M$ is the mass ratio between the secondary and primary.

3.1. V404 Cyg

The dynamical parameters of this black hole SXT are relatively well constrained: $M \sim 12M_\odot$, $M_{sec} \sim 0.7M_\odot$ (Shahbaz et al. 1994), $q = 0.0583$, which give $R_{sec}/a = 0.176$, $\Omega_{-2} = 0.777$. The observed Li abundance in the secondary is $\log(n_{Li}/n_H) = -9.4$ (Martin et al. 1994a). Narayan, Barret & McClintock (1997) fitted the X-ray and optical spectrum of V404 Cyg in quiescence and estimated a mass accretion rate of $\dot{m} = 0.0046$ for $\alpha = 0.3$. If we take the mass in the envelope of the secondary to be $0.2M_{sec}$, and assume that the Li in the secondary is in steady state, then equation (2-14) gives

$$F_{esc} \sim 5.4 \times 10^{-4} \left(\frac{M_{env}}{0.14M_\odot} \right) \left(\frac{10^8 \text{yr}}{t_D} \right). \quad (3-2)$$

Alternatively, if we assume that the depletion time is longer than the X-ray lifetime of the system, we obtain from equation (2-15)

$$F_{esc} \sim 4.7 \times 10^{-4} \left(\frac{M_{env}}{0.14M_{\odot}} \right) \left(\frac{0.14M_{\odot}}{\Delta M} \right). \quad (3-3)$$

With either estimate we see that there needs to be only a very small level of mass ejection, of the order of 0.1% of the mass accretion rate, in order to contaminate the secondary with the observed level of Li. Even if the Li depletion time in the secondary is as short as 10^7 yr, the fraction of escaping material still has to be only about 1% of the accreted mass. In fact, since Pinsonneault et al. (1992) suggest a long depletion time $\sim 10^9$ yr, the parameter F_{esc} may be as small as 10^{-4} . Thus, spallation in the hot ADAF during the quiescent state of V404 Cyg is a very promising mechanism to explain the observed Li excess in the secondary.

3.2. A0620-00 and Other Similar Systems

We adopt the following system parameters: $M = 6M_{\odot}$, $M_{sec} = 0.5M_{\odot}$ (Barret, McClintock & Grindlay 1996), $q = 0.0833$, which give $R_{sec}/a = 0.196$, $\Omega_{-2} = 0.960$. The observed Li abundance is $\log(n_{Li}/n_H) = -10$ (Martin et al. 1994a).

Narayan, McClintock & Yi (1996) fitted the X-ray and optical spectra of A0620-00 and estimated $\dot{m} = 2 \times 10^{-4}$ for $\alpha = 0.3$. The steady state value of F_{esc} is then

$$F_{esc} \sim 0.083 \left(\frac{M_{env}}{0.1M_{\odot}} \right) \left(\frac{10^8 \text{yr}}{t_D} \right). \quad (3-4)$$

Note, however, that the Narayan et al. (1996) model was based on a black hole mass of $4.4M_{\odot}$ and corresponded to $\beta = 0.95$. A reanalysis, with $M = 6.1M_{\odot}$, $\beta = 0.5$, and making use of the improved modeling techniques described in Narayan et al. (1997), gives $\dot{m} = 9.7 \times 10^{-4}$. For this value of $\dot{m}$, assuming steady state, we find

$$F_{esc} \sim 3.5 \times 10^{-3} \left(\frac{M_{env}}{0.1M_{\odot}} \right) \left(\frac{10^8 \text{yr}}{t_D} \right), \quad (3-5)$$

while for the case when depletion can be neglected we find

$$F_{esc} \sim 4.6 \times 10^{-4} \left(\frac{M_{env}}{0.1M_{\odot}} \right) \left(\frac{0.1M_{\odot}}{\Delta M} \right). \quad (3-6)$$

As in the case of V404 Cyg, we see that we need about 0.1% of the accreted mass to be ejected (1% if $t_D = 10^7$ yr) in order to produce the observed level of Li in the secondary.

The black hole SXTs, GS2000+25 and Nova Mus 1991, are fairly similar to A0620-00 in their binary parameters: $M = 6 - 14M_{\odot}$, $M_{sec} = 0.2 - 0.6M_{\odot}$ (Filippenko et al. 1995, Harlaftis et al. 1996, Barret et al. 1996). The observed Li abundances in the secondaries also agree to within an

order of magnitude (Harlaftis et al. 1996). There are no reliable models yet of these systems in quiescence, and we do not have an independent estimate of $\dot{m}$. The observed Li requires that $\dot{m}$ in quiescence should be similar to the values we have estimated for V404 Cyg and A0620-00.

3.3. Cen X-4

This neutron star SXT has the highest observed Li abundance among all SXTs, $\log(n_{\text{Li}}/n_{\text{H}}) = -8.7$ (Martin et al. 1994a). We take the following system parameters: $M = 1.4M_{\odot}$, $M_{\text{sec}} = 0.1M_{\odot}$ (McClintock & Remillard 1990), $q = 0.0714$, which give $R_{\text{sec}}/a = 0.187$, $\Omega_{-2} = 0.874$.

The mass accretion rate in the system is uncertain. The observed quiescent X-ray luminosity of $\sim 2.4 \times 10^{32} \text{ erg s}^{-1}$ (Asai et al. 1996) implies a very low $\dot{m} \sim 10^{-6}$. Equations (2-14) and (2-15) show that it is impossible with such a low $\dot{m}$ to produce the observed level of Li. Could $\dot{m}$ be substantially larger?

Since Cen X-4 is a neutron star system, we need to consider the possibility that the star may have a moderately strong surface magnetic field. Coherent pulsation with a period of $P_* = 31.28$ ms may have been observed in this system in quiescence (Mitsuda et al. 1996). The signal is most likely due to the rotation of the neutron star, and indicates the likely presence of a magnetosphere (e.g. Frank et al. 1992). ADAFs have been shown to have a substantially sub-Keplerian rotation (Narayan & Yi 1994, 1995b), $\Omega = c_2(GM/R^3)^{1/2}$, where the coefficient c_2 is given in Narayan & Yi (1995b). For $\alpha = 0.3$, $\beta = 0.5$, we obtain $c_2 = 0.417$. Taking the measured spin period in Cen X-4, the corotation radius is

$$r_c = R_c/R_s = c_2^{2/3}(GMP_*^2/4\pi^2)^{1/3}/(2GM/c^2) \sim 22, \quad (3-7)$$

while the magnetospheric radius (or Alfven radius) for a surface magnetic field strength B_* is

$$r_A = R_A/R_s \sim 44 \left(\frac{B_*}{10^9 G} \right)^{4/7} \left(\frac{\dot{M}}{10^{15} g/s} \right)^{-2/7}. \quad (3-8)$$

If $B_* \sim 10^9 (\dot{M}/10^{15} \text{ g s}^{-1})^{1/2} G$ (a reasonable value based on the field strengths seen in millisecond pulsars), then it is quite possible that Cen X-4 in quiescence has its magnetospheric radius somewhat outside the corotation radius. If r_A is sufficiently large (> 50), the system could be in the “propeller regime” (Illarionov & Sunyaev 1975), where the bulk of the accreted material is stopped by the magnetic field and flung out by centrifugal action (Asai et al. 1996, Tanaka & Shibazaki 1996).

The existence of a propeller enhances the predicted Li in the secondary in two ways. First, if there is a propeller, the mass accretion rate is much higher than that inferred from the X-ray luminosity, since only a very small fraction of the accreting material actually reaches the neutron star. This obviously increases the Li yield in the accretion flow (eq 2-11). Second, the propeller

action ensures that essentially all the accreting material is thrown out, so that we expect the parameter F_{esc} to be essentially of order unity. Thus, a much larger fraction of the Li produced in the accretion ends up on the secondary. There is a counter-effect, however. If the magnetospheric radius is larger than the critical radius $r_{out} = 33.8$ calculated in sec. 2.3, then very few alpha particles achieve the energy (~ 8.5 MeV per nucleon) needed for spallation, and the Li yield is less than in the black hole case.

Let us assume that the bulk of the mass flow is stopped by the magnetospheric pressure at $r = r_A$ and expelled through the propeller effect. We take $r_A \sim 50$, the radius at which the centrifugal action is just able to drive the accreted material to infinity. Although for $r \geq 33.8$ the mean energy per nucleon is below the $\alpha - \alpha$ spallation threshold, some Li can still be produced by alpha particles in the high energy tail of the particle energy distribution. To estimate the reaction rate we need to do a more careful calculation than we did in sec. 2.3. Adopting a Maxwellian distribution (this is just a convenient model and the real distribution may be quite different), the effective interaction rate is given by

$$\langle \sigma_+ v \rangle = \int n(E) \sigma_+(E) v(E) dE, \quad (3-9)$$

where

$$n(E) dE = \frac{2}{\sqrt{\pi} (kT)^{3/2}} \exp(-E/kT) E^{1/2} dE \quad (3-10)$$

(e.g. Cox & Giuli 1968), and $v(E) = \sqrt{2m_u E}$. Carrying out the integral over energy and radius, we find that the abundance of Li when the accretion flow reaches $r = 50$ is

$$\frac{n_{Li}}{n_H} = 2.33 \times 10^{-5} \frac{\dot{m}}{\alpha^2}. \quad (3-11)$$

The Li yield is lower by a factor ~ 90 than for the case considered in sec. 2.3 (eq. 2-10). The inefficiency arises because the flow is truncated before it can reach the optimum radius ($r \sim 30$) for spallation. Incidentally, if we allow the flow to extend down to $r = 1$, the present more detailed calculation gives a coefficient of 2.66×10^{-3} in equation 2-10, instead of 2.12×10^{-3} ; thus, the simplifying assumption made in sec. 2.3 leads to an error of about 20%. If we truncate the accretion flow at a radius $r \sim 10^3$, as appropriate for an accreting white dwarf, there is no Li production at all by spallation. Thus, the absence of Li in CVs (Martin et al. 1994a) is naturally explained in this model.

With the lower Li yield given in equation (3-11), equation (2-14) is modified to

$$F_{esc} = 2.00 \times 10^{-4} \frac{\alpha^2}{m \dot{m}^2} \frac{M_{env,-1}}{\Omega_{-2} t_{D8}} \left(\frac{n_{Li}}{n_H} \right)_{-9}. \quad (3-12)$$

Let us assume that $F_{esc} = 1$ in Cen X-4 because of the propeller effect. Then, setting $\alpha = 0.3$ and substituting the values of the various other quantities, we can solve for $\dot{m}$:

$$\dot{m} = 2.3 \times 10^{-3} \left(\frac{M_{env}}{0.02 M_\odot} \right)^{1/2} \left(\frac{10^8 \text{yr}}{t_D} \right)^{1/2}. \quad (3-13)$$

Alternatively, if we assume that the depletion time is very long and use the equivalent of equation (2-15), we obtain

$$\dot{m} = 8.1 \times 10^{-4} \left(\frac{M_{env}}{0.02 M_{\odot}} \right) \left(\frac{0.02 M_{\odot}}{\Delta M} \right). \quad (3-14)$$

The two estimates are roughly consistent with each other, and in fact give quite a reasonable value of $\dot{m}$, since it is quite similar to the values of $\dot{m}$ we have estimated in V404 Cyg and A0620-00. Black hole SXTs and neutron star SXTs are quite similar to each other in many respects. We might, therefore, expect their mass accretion rates (scaled to the Eddington value) to be similar, both in quiescence and outburst. As supporting evidence we note that Cen X-4 and A0620-00 seem to be similar to each other in their outbursts. Cen X-4 has had two outbursts in the last 30 years with a total X-ray output of about $\text{few} \times 10^{44}$ ergs, which is fairly similar to the energy output of A0620-00 during a similar period (Tanaka & Shibazaki 1996). This suggests that the mass storage rates in the two systems are comparable. It is reasonable to think that the quiescent accretion rate in Cen X-4 also is roughly the same as in A0620-00, i.e. $\dot{m} \sim 10^{-3}$. Since this is more-or-less the value we need to explain the observed Li in Cen X-4, we argue that the scenario is consistent.

3.4. Soft X-Ray Transients in Outbursts

In addition to the quiescent state which we have considered so far, Li may also be produced during periods of more rapid mass accretion in outbursts (see Tanaka & Shibazaki 1996 for a discussion of SXT outbursts). The hot ADAF solution on which we have based our estimates exists only for $\dot{m} < \dot{m}_{crit} \sim (0.3 - 1)\alpha^2$ (Narayan & Yi 1995b). We need, therefore, to determine exactly when during an outburst the accretion is in the form of an ADAF. At the peak of the outburst, the mass accretion rate in SXTs approaches the Eddington limit, $\dot{m} \rightarrow 1$. During this period the accretion will most likely be in the form of a thin disk (cf. Narayan 1996) and therefore not suitable for producing Li. However, both when the system is on its way up to the peak and on its way down from the peak, the flow will go through a period of advection-dominated accretion with $\dot{m}$ close to the limiting $\dot{m}_{crit}$. The rise to outburst is usually quite rapid and not very interesting, but the decline is often slower, and it is likely that SXTs linger around $\dot{m} \sim \dot{m}_{crit}$ for a reasonable period of time during decline. During this period, Li synthesis could be particularly efficient (since eq. 2-11 shows that Li production varies as $\dot{m}^2$). Using the subscript “high” to refer to episodes of $\dot{m} \sim \dot{m}_{crit}$ and the subscript “low” for the quiescent state, we estimate the relative Li production in the two phases to be

$$\frac{M_{Li}(high)}{M_{Li}(low)} \sim \left(\frac{\Delta t_{high}}{\Delta t_{low}} \right) \left(\frac{\dot{m}_{high}}{\dot{m}_{low}} \right)^2 \left(\frac{\alpha_{high}}{\alpha_{low}} \right)^{-2} \left(\frac{F_{esc,high}}{F_{esc,low}} \right), \quad (3-15)$$

where Δt , α , and F_{esc} refer to the duration, the viscosity parameter, and the ejection fraction. Taking typical time scales, $\Delta t_{high} \sim 0.1$ yr and $\Delta t_{low} \sim 30$ yr, and assuming that α and F_{esc} in

the two phases are the same, we find that the amount of Li produced in the high phase exceeds that produced in the low phase if

$$\left(\frac{\dot{m}_{high}}{\dot{m}_{low}}\right) > 17 \left(\frac{\Delta t_{low}/\Delta t_{high}}{300}\right)^{1/2}. \quad (3-16)$$

In view of the values of $\dot{m}_{low}$ we have estimated (see secs. 3.1–3.3) and the likely value of $\dot{m}_{high}$ ($\sim 0.03–0.1$ for $\alpha = 0.3$), we infer that Li production during outbursts could be competitive with production during quiescence, and might even dominate. To see this another way, we follow the methods described in sec. 2.4 and estimate the equilibrium abundance of Li in the secondary purely as a result of outbursts:

$$\frac{n_{Li}}{n_H} \sim \frac{\Delta M_{Li} t_D}{7 \times 0.75 M_{env} t_{rec}} \sim 1.4 \times 10^{-10} m \left(\frac{\Omega}{10^{-2}}\right) \left(\frac{F_{esc}}{10^{-3}}\right) \left(\frac{t_D}{10^8 \text{ yr}}\right) \left(\frac{0.1 M_\odot}{M_{env}}\right) \left(\frac{300}{\Delta t_{low}/\Delta t_{high}}\right), \quad (3-17)$$

where we have used $\alpha = 0.3$ and $\dot{m}_{high} = \alpha^2 = 0.09$. We find that the predicted Li abundance due to outbursts is comparable to the observed values.

Thus, we conclude that Li production during outbursts could be important and has to be considered seriously. However, the exact variation of $\dot{m}$ during the decline from outburst is not well understood and it is not clear exactly at which stage of the decline the accretion switches from a thin disk to an ADAF. In view of this uncertainty, the estimates given here are less reliable than the values given earlier for quiescent SXTs.

3.5. Observing Gamma-Ray Lines from Excited Li

In some black hole X-ray binaries such as Nova Mus 91 and 1E 1740.7-2942, a gamma-ray line feature near ~ 480 keV has been reported (e.g. Goldwurm et al. 1992, Bouchet et al. 1991), which is interestingly close to the gamma-ray emission line (478 keV) expected from excited ${}^7\text{Li}$ in spallation (Martin et al. 1992b, 1994ab). As we have shown in sec. 2.5, however, gamma-ray line emission from ADAFs in X-ray binaries has a maximum luminosity of only $\sim 10^{33} \text{ erg s}^{-1}$, even if we ignore the loss of Li into the black hole, whereas the line detected in Nova Mus 91 had a luminosity of $10^{37} \text{ erg s}^{-1}$ for an assumed distance of 5 kpc. Another problem is that the line in Nova Mus 91 was observed at a time when the system was either in the “high” or “very high” state. These states are likely to involve accretion via a thin accretion disk (cf. Narayan 1996) for which the present analysis is not relevant.

3.6. Lithium Production in Other Black Hole Systems

Cyg X-1 is a bright X-ray binary which very likely undergoes accretion via an ADAF (at least in the “low state”, cf. Narayan 1996). The X-ray luminosity of the source is $\sim \text{few} \times 10^{37} \text{ erg s}^{-1}$,

which corresponds to $\dot{m} \sim 0.1$ for a black hole mass of $\sim 10M_\odot$. By the estimates given in this paper, Cyg X-1 must be producing a large quantity of Li, of which substantial amounts must be intercepted by the secondary. If the depletion time is not different from that in other stars, and if the Li is not swept away by the strong wind from the star, the abundance of Li in the secondary must be fairly high. Unfortunately, the star is too hot to reveal Li in its spectrum, and so this prediction cannot be tested.

At the current level of activity, $\dot{m} \sim 10^{-3}$ (Narayan, Yi & Mahadevan 1995), the Galactic center source Sgr A* ($M \sim 10^6 M_\odot$) would produce $\sim 30M_\odot$ of ${}^7\text{Li}$ over its life time of $\sim 10^{10}$ yr (cf. eq 2-10), of which about $0.03M_\odot$ would be ejected into the surrounding ISM, assuming $F_{esc} \sim 10^{-3}$. If the source was more active in the past than it is at present, the Li enrichment near the Galactic center could be even larger (since $\dot{M}_{Li}$ varies quadratically with $\dot{m}$, see eq 2-11). If the ejected Li does not diffuse too far from the Galactic Center there may be some evidence for excess Li in newly formed stars in the region. At the current level of activity, the gamma-ray line emission from Sgr A* is expected to be only $L_\gamma \sim 5 \times 10^{33} \text{ erg s}^{-1}$.

4. Discussion

In this paper, we have considered Li production through spallation in hot ADAFs in SXTs, concentrating primarily on the quiescent state of SXTs (secs. 2.1–2.4). The ADAF paradigm has been applied successfully to two black hole SXTs, V404 Cyg and A0620-00, and provides a good description of the observed spectra in these systems in quiescence (Narayan et al. 1996, 1997). The models are well constrained by the observations and provide all the parameters necessary in these two SXTs for a quantitative estimate of the Li yield via spallation. The only uncertainty at this point concerns the parameter F_{esc} , which is defined such that $F_{esc}\Omega$ is the fraction of the accreting material which reaches the secondary via an outflow, where Ω is the solid angle subtended by the secondary as viewed from the accreting star. We find that we can fit the observed Li abundances in the secondaries of V404 Cyg and A0620-00 if we assume that $F_{esc} \sim 10^{-3}(10^8 \text{ yr}/t_D)$, where t_D is the time scale on which Li is depleted in the envelope of the secondary. Since t_D is expected to be in the range $10^7 - 10^9$ yr, with the longer time scale more likely (Pinsonneault 1992), the required ejection fraction is small, making the scenario quite plausible. Moreover, we find that we need similar values of F_{esc} in V404 Cyg and A0620-00, which shows that the model is consistent.

A natural consequence of our model is that Li synthesis takes place only in accretion flows around black holes and neutron stars, but not around white dwarfs. The spallation reactions need about 10 MeV per nucleon, and white dwarf accretion flows do not reach such temperatures even when they are advection-dominated. Martin et al. (1995) found that CVs with late type secondary stars similar to those in SXTs do not show Li (Martin et al. 1994a). This is consistent with our model.

We find that Li production during outbursts of SXTs could be quite important, and may

perhaps even dominate over the production during quiescence (sec. 3.4). However, it is not known exactly when during outburst the accretion occurs as an ADAF and when as a thin disk. Since the high temperatures needed for spallation are present only in ADAFs, the estimate of the Li yield is somewhat uncertain.

In principle, Li could be produced even when the accretion is via a thin disk (say at the peak of an outburst) in nonthermal flares (Field & Rogers 1993) or in an active corona. Another possibility is that the bulk motion of the ejected material (either during quiescence or outburst) may be fast enough that when the ejected alpha particles reach the secondary they produce spallation reactions in situ in the envelope of the secondary (Rytler 1970). The uncertainties in such models are, however, quite severe, and it is very hard to make quantitative estimates of the Li yield. Yet another possibility is that supernova explosions of the progenitor stars might contaminate the secondaries with Li (Dearborn et al. 1989). However, in some models the progenitors of black holes collapse without explosions (e.g. Woosley 1993 and references therein). We do not expect Li contamination of the secondary in such models.

While our spallation scenario works well for quiescent black hole SXTs, a direct application of the model to the neutron star SXT, Cen X-4, fails by many orders of magnitude. The X-ray luminosity of Cen X-4 in quiescence is very low. As a result, when we determine the mass accretion rate $\dot{m}$ directly from the luminosity, we find that the estimated Li production is extremely low. One solution could be that Cen X-4 produces most of its Li during outbursts. We, however, prefer a second solution, namely that Cen X-4 may be accreting via a propeller mode (Illarionov & Sunyaev 1975), as argued by Asai et al. (1996) and Tanaka & Shibazaki (1996).

We suggest that Cen X-4 has quite a high $\dot{m} \sim 0.002$ in quiescence, similar to the accretion rate we have estimated in V404 Cyg and A0620-00 from spectral fitting (secs. 3.1, 3.2). However, most of the accreting mass is flung out by the centrifugal action of the rotating neutron star. Since only a tiny fraction of the mass accretes on the neutron star, the low X-ray luminosity is explained. Furthermore, since nearly all the accreting mass flows out, the amount of Li reaching the secondary is larger than in the black hole systems. Thus, the propeller model naturally explains the unusually high abundance of Li in Cen X-4.

One could make a plausible argument that quiescent neutron star SXTs are especially likely to be in the propeller regime. A typical SXT has its mass accretion rate varying by three or more orders of magnitude between quiescence and outburst. By equation (3-8), the magnetospheric radius r_A should vary by nearly an order of magnitude, moving in during outburst and moving out in quiescence. Let us assume that the neutron star attains some kind of equilibrium spin period appropriate to its mean mass accretion rate. During outburst, we will have $r_A < r_c$ (the corotation radius, cf. eq. 3-7) and the neutron star will undergo spin-up. However, during quiescence, we expect $r_A > r_c$ and it is quite likely that we will have spindown via propeller action.

In our model, Cen X-4 in quiescence has a large mass outflow rate, $\dot{M}_{out} \sim 2 \times 10^{15} \text{ g s}^{-1}$, and the outflow velocity is on the order of the rotation speed at the magnetospheric radius, $v_{out} \sim 0.1c$.

These estimates are based on the tentative rotation period of the neutron star, $P_* = 31.28$ ms, identified by Mitsuda et al. (1996). The presence of an energetic outflow in Cen X-4 may perhaps be detectable. For instance, the gas may produce weak radio emission via synchrotron radiation of shock-accelerated electrons. Cen X-4 was detected as a ~ 10 mJy radio source during one of its outbursts (Hjellming et al. 1988). Conceivably, the source may be visible even in quiescence as a much weaker radio source. Another possibility is that the ejected material may produce nebular emission when it shocks with the ISM. We note in this connection that Kulkarni & Hester (1988) detected an H α nebula around the radio pulsar, PSR 1957+20; the nebula in that case arises from the interaction of the pulsar wind with the ISM. The kinetic energy flux in PSR 1957+20 is estimated to be about 10^{35} erg s $^{-1}$, while in Cen X-4 we estimate a flux of $\sim 10^{34}$ erg s $^{-1}$. Because of the propeller effect, we expect Cen X-4 in general to have stronger evidence of outflow-related activity than A0620-00, even though the two systems have similar $\dot{m}$. (In fact, in physical units, A0620-00 has a higher $\dot{M}$ than Cen X-4 because of its larger mass.)

Another consequence of our model of Cen X-4 is that the X-ray pulsations detected in this system (Mitsuda et al. 1996) should reveal a secular spin-down of the neutron star. Using our model parameters and a neutron star moment of inertia $I_* \sim 10^{45}$ g cm 2 , we estimate the spindown time scale to be $P_*/\dot{P}_* \sim I_*\Omega_*/\dot{M}\Omega(R_A)R_A^2 \sim 10^8$ yr.

One interesting point is that Cen X-4, which has the highest Li abundance among the three SXTs studied so far (and indeed one of the highest abundances seen in any star), may be relatively inefficient at producing Li. According to our model, the magnetospheric radius in this system is fairly large, $r_A \sim 50$, and lies outside the optimal radius ~ 30 for Li spallation. Thus, for the given $\dot{m}$, the accretion flow in Cen X-4 produces about 90 times less Li than an equivalent black hole system would (sec. 3.3, but note that the argument is based on the tentative rotation period of 31.28 ms measured by Mitsuda et al. 1996). If we could find another neutron star SXT, with a weaker magnetic field than Cen X-4 such that $r_A < 30$, then the Li yield would be substantially higher. If the system were to have an active propeller in quiescence (which we argued earlier is likely), then we could easily imagine a steady state Li abundance in the secondary on the order of $n_{\text{Li}}/n_{\text{H}} \sim 10^{-8} - 10^{-7}$. The discovery of such an object would prove beyond any reasonable doubt that the Li in SXT secondaries is produced by the accretion flow, and would rule out the alternative hypothesis that the Li is a fossil left-over from the initial material of the star. If a neutron star in an SXT has a stronger magnetic field than Cen X-4 and if r_A exceeds ~ 60 say, then the Li yield would be vanishingly small. Thus, we expect an inverse correlation between the magnetic field strength (or equivalently the equilibrium spin period of the neutron star) and the Li abundance of the secondary. The correlation is not likely to be linear, however, but more in the nature of a step function.

Two outstanding uncertainties in the spallation scenario we have outlined should be mentioned.

- (i) The Li depletion time scale in the secondary is poorly constrained. While we have shown

that the model works even with a time scale as short as $\sim 10^7$ yr, as is commonly assumed for K type main sequence stars, it would be useful to have a better handle on this parameter. For instance, if the depletion time scale is much longer than the age of the binary system (Duncan 1981, Pilachowski et al 1984, Boesgaard & Steigman 1985, Pinsonneault et al. 1992), say as a result of tidal effects (cf. Zahn & Bouchet 1989, Zahn 1994), then it is conceivable that the Li we see in SXTs is just the Li with which the secondary was originally formed. This hypothesis is not very attractive in view of the fact that secondaries in CVs do not have detectable levels of Li (Martin et al. 1995), but cannot be ruled out conclusively at present.

(ii) A major uncertainty in our model is the angular distribution of the ejected material. If most of the ejection occurs along the poles, then even the small values of F_{esc} which we require in our scenario may be difficult to achieve. A further uncertainty is that ejecta from the accretion flow may be unable to penetrate the secondary star if the latter has a magnetosphere or an active wind. One positive feature of the model is that outflows are considered natural and even likely in ADAFs (Narayan & Yi 1994, 1995a). In view of these uncertainties, our results can be stated that we need a fraction $\sim 10^{-5}(10^8\text{yr}/t_D)$ of the accreting mass be intercepted by the secondary stars in V404 Cyg and A0620-00 after Li production has taken place. In the case of Cen X-4 we need $\sim 10^{-2}(10^8\text{yr}/t_D)$ to reach the secondary.

Martin et al. (1992b, 1994b) made the interesting suggestion that gamma-ray lines from excited Li and Be nuclei produced by spallation may be detectable and may in fact be the origin of a spectral line at 480 keV detected in Nova Mus 91 and 1E 1740.7-2942 (Goldwurm et al. 1992, Bouchet et al. 1991). Since the gamma-ray line luminosity is independent of both of the uncertainties mentioned above (namely depletion time scale and F_{esc}), we are in a position to estimate the luminosity fairly accurately (sec. 2.5). We find that, even under the most optimistic of circumstances, the calculated flux is much below the detection thresholds of present instruments (though perhaps detectable by the Ge spectrometer planned for the INTEGRAL mission). Thus, at least within the ADAF paradigm, we can rule out the suggestion of Martin et al. However, as we have mentioned earlier, Li could conceivably be produced during SXT outbursts by a different process for which our ADAF-based estimates may not be applicable.

The abundance of Li in Pop I material in the Galaxy is about $\log(n_{Li}/n_H) \sim -9$, whereas the primordial abundance as measured in halo stars is significantly lower, $\log(n_{Li}/n_H) \sim -9.8$ (Boesgaard & Steigman 1985). What is the origin of the extra Li in the Galactic disk? Cosmic ray spallation alone cannot explain the observations, and it is proposed that there needs to be an anomalous component of low energy cosmic rays with energy $\sim$ tens of MeV per nucleon (e.g. Reeves et al. 1990). ADAFs provide precisely the kind of environment and particle energies needed by the observations and it is interesting to ask if Li production in accreting black holes or neutron stars could be a significant source of the Li observed in the Galaxy.

If we take the total baryonic mass of the Galactic disk to be $\sim 10^{11}M_\odot$, then the mass of Li is $\sim 7 \times 10^{-9} \times 0.75 \times 10^{-11}M_\odot \sim 500M_\odot$. The rate at which Li is ejected into the ISM by an

accreting black hole is given by equation (2-11) multiplied by the escape fraction F_{esc} , i.e.

$$\dot{M}_{Li} = 2.47 \times 10^{-10} F_{esc} \frac{m\dot{m}^2}{\alpha^2} M_{\odot} \text{ yr}^{-1}. \quad (4-1)$$

Even by using quite optimistic estimates of the various parameters, we find that it is very hard to produce $500M_{\odot}$ of Li during the life of the Galaxy from known accreting systems. We consider four cases:

(i) For black hole SXTs, we have $m \sim 10$, $\dot{m} \sim 0.003$, $\alpha \sim 0.3$. If we assume that the integrated Li production from outbursts is 10 times larger than during quiescence (cf. eq. 3-16), and if we take a large $F_{esc} \sim 0.1$, then we still obtain only $\sim 2.5 \times 10^{-13} M_{\odot} \text{ yr}^{-1}$ of Li from a single SXT. The Galaxy needs to have a steady population of $\sim 2 \times 10^5$ active SXTs over the lifetime of the Galaxy to produce the observed Li. Current estimates of the SXT population are, however, only $\sim \text{few} \times 10^3$ active systems (Tanaka & Shibazaki 1996 and references therein).

(ii) Consider Cyg X-1 like objects: $m \sim 10$, $\dot{m} \sim 0.1$, $\alpha \sim 0.3$. Again, taking $F_{esc} \sim 0.1$, we need about 2000 active objects at any given time to produce the required Li. The number of bright X-ray binaries in the Galaxy is only $\sim 10^2$, and only a small fraction of these are Cyg X-1 like objects.

(iii) For neutron star SXTs, we optimistically assume that most of the systems have $r_A < 30$ in quiescence and are therefore as efficient as the black hole systems at producing Li. Setting $m = 1.4$, $\dot{m} \sim 0.003$ (optimistic), $\alpha \sim 0.3$, $F_{esc} \sim 1$ (assuming a propeller), each system ejects $\sim 3.5 \times 10^{-14} M_{\odot} \text{ yr}^{-1}$ of Li into the ISM. We need a steady population of over 10^6 active objects to explain the observed Li in the Galactic disk, which seems unlikely.

(iv) Finally, we consider the black hole at the Galactic Center. We have shown in sec 3.5 that the current level of activity would produce very little ^7Li during the age of the Galaxy $\sim 10^{10}$ yr. Li production at the Galactic Center becomes interesting only if the Galaxy has experienced an active accretion episode in the past, similar to that in Seyfert galaxies. Let us assume that the present mass of the black hole ($m \sim 2.5 \times 10^6$) was accumulated primarily during episodes of $\dot{m} \sim 0.1$ lasting for a total duration of $\sim 4.5 \times 10^8 \text{ yr}$. Then equation (4-1) suggests that such a source would have ejected $\sim 3 \times 10^3 M_{\odot}$ of ^7Li for $\alpha = 0.3$ and $F_{esc} = 0.1$, which is more than enough to account for the total mass of Li in the Galactic disk.

We thus conclude that none of the known populations of X-ray binaries in the Galaxy is capable of supplying the observed Li in Pop I stars. A period of active accretion in the past at the Galactic Center could have ejected sufficient Li, but it is unclear if the Li would have spread over the entire disk.

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