Astron. Astrophys. 330, 999–1004 (1998)

ASTRONOMY AND ASTROPHYSICS

The Li I resonance line in the spectra of X-ray nova accretion discs

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Received 11 July 1997 / Accepted 29 August 1997

Abstract. We study the formation of the Li I λ 6708 Å resonance doublet in spectra of X-ray novae during the stage of outburst decay. We discuss the general conditions on accretion disc parameters which allow the detection of any spectral line absorption component in spectra of self-irradiated accretion discs. We obtain a simple analytical formula to estimate the equivalent width of the lithium line in the spectra of these discs and, adopting a simple model of self-irradiation, we have conducted more precise numerical calculations of these equivalent widths in the spectra of accretion discs around Schwarzschild black holes. We find that the equivalent width of the Li I doublet can reach $\sim$ 20–100 mÅ during outburst decay if the luminosity becomes less than 0.01 Eddington luminosity and if the lithium abundance in the discs is about cosmic (log N(Li)$\sim$3). If some lithium production takes place in these discs higher abundances would be possible and consequently stronger lines could be formed. The larger the outer disc radius and the smaller the disc inclination angle to line of sight, the greater the equivalent width of the line.

Key words: accretion discs – stars: abundances – novae – X-rays: stars

1. Introduction

X-ray novae are a subclass of binaries formed by a compact primary – a black hole or a neutron star – and a F-M type dwarf or subgiant. They are characterized by undergoing strong X-ray and optical outbursts every 10–50 years. (e.g. Bradt & McClintock 1983). These outbursts appear to be connected with an increase in the accretion rate on to the primary which can be caused by an instability in the outer disc (Lin & Taam 1984) or by a sudden increase in the mass-transfer from the secondary (Hameury et al. 1986). The X-ray spectra of these particular objects are similar to that of Cyg X-1, one of the first black hole candidates (Sunyaev et al. 1991). Indeed, many of the best black hole candidates have been found in X-ray novae. We may list, among others, A0620-00 = V 616 Mon (McClintoc & Remillard 1986), XN Mus 1991 = GRS 1121-68 (Remillard et al. 1992), V 404 Cyg = GS 2023+338 (Casares et al.1992).

The optical radiation of X-ray novae is mostly associated with the reprocessing of the inner disc hard radiation by the outer disc and secondary star, as suggested by the numerous emission lines in their spectra (Della Valle et al. 1991). Nevertheless, it is possible to observe Balmer lines in absorption in the optical spectra during the outburst decay (Suleimanov 1996). Such absorption lines have been seen, for example, in the spectra of GRO J0422+32 (Shrader et al. 1994; Callanan et al. 1995) and XN Vel 1993 (Della Valle et al. 1997). The study of disc absorption lines can provide a powerful diagnostic of the physical conditions of the accretion disc as well as detailed information on its chemical composition. In particular, the formation of disc absorption lines may be relevant to the investigation of the origin of the high Li abundances found in the secondary stars of several X-ray novae (Martín et al. 1992, 1994). One possible explanation for these high abundances, first suggested by Martín et al. (1992), is that Li would be originated by $\alpha - \alpha$ collisions and spallation reactions in the accretion disc around the compact object or in the secondary itself. This scenario can be tested through the detection of γ emission lines at 470 keV associated with de-excitation of the ^{7}Li nuclei produced by $\alpha - \alpha$ reactions. In this respect, the observed emission line at 476 $\pm$ 15 keV in the spectrum of XN Mus 1991 (Sunyaev et al. 1992) and the recent detection of Li in the secondary of this system (Martín et al. 1996) are remarkable. An alternative method of testing this scenario would be the detection of high Li abundances in the accretion disc itself. In this paper, we examine the formation of the Li I λ 6708 Å resonance line in the spectra of X-ray novae during outburst decay. It is found that detection is feasible provided the abundance in the disc is as high as in the atmospheres of the secondaries log N(Li)$\sim$ 2-3.5 (in the usual scale where log N(H) = 12).

The formation of spectral lines in accretion discs has been investigated by many authors. For example, the works by Herter et al. (1979), Mayo et al. (1979), Williams (1980) and la Dous (1989) were devoted to the modelling of absorption lines in the spectra of accretion discs around white dwarfs. These authors assumed that each disc ring radiates as a stellar atmosphere

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with the same effective temperature $T_{\rm eff}$ and surface gravity log g. However, this approach does not explain the emission cores of the absorption lines, and to surmount this problem Tylenda (1981) took into account self-irradiation of the disc and irradiation by the boundary layer, and Cheng & Lin (1989,1992) took into consideration optically thin parts and a "chromosphere-like" temperature distribution in the accretion disc atmosphere. The emission spectra of low-mass X-ray binaries (LMXB) accretion discs irradiated by X-rays have been calculated by Ko & Kellman (1994) with the use of the photon escape probability method.

In our work we have chosen a simple method of considering the self-irradiation of the disc which takes into account the available constraints on the parameters of accretion discs (Sect. 2). This approach does not allow the exact calculation of spectral lines, but it does to estimate the maximum possible equivalent width of any absorption line component. Our results for the Li I λ 6708 and the H_β lines have been obtained in Sect. 3 and the discussion and conclusions are presented in Sect. 4.

2. Formation of absorption lines in the spectra of self-irradiated discs

Let us first describe the method used to calculate the total radiation spectrum of self-irradiated, optically thick, geometrically thin, accretion discs (Suleimanov 1992, 1996). We denote as F_ν the final spectrum that results from the addition of the individual local ring spectra $I_\nu(R,i)$:

$$F_\nu = 2\pi \cos i \int_{\rm R_{in}}^{\rm R_{out}} I_\nu(R,i) R dR, \quad (1)$$

where i is the inclination angle of the disc with respect to the line of sight, R is the radius of the local ring and $R_{\rm in}$ and $R_{\rm out}$ are the inner and outer boundary disc radii, respectively.

For $I_\nu(R,i)$, we will adopt the spectrum of a stellar atmosphere with the same effective temperature $T_{\rm eff}$ and log g, provided that the ring effective temperature is less than 50000 K and the relation of incident X-ray flux $F_{\rm irr}$ to intrinsic ring flux F_0 is less than a certain critical parameter A. If these conditions do not hold, the ring is assumed to radiate as a black body with a temperature equal to $T_{\rm eff}(R)$.

The intrinsic ring flux is determined by the following equation (Shakura & Sunyaev 1973):

$$F_0(R) = \sigma T^4_{\rm eff}(R) = \frac{3}{8\pi}\frac{GM\dot{M}}{R^3}[1-(\frac{R_{\rm in}}{R})^{1/2}], \quad (2)$$

where M is the mass of the central compact object and $\dot{M}$ is the accretion rate.

The incident flux is described following Ko & Kellman (1991) as:

$$F_{\rm irr}(R) = f\eta\frac{\dot{M}c^2}{4\pi R^2}, \quad (3)$$

where η is the energy conversion factor, c is the speed of light and f is the fraction of the total incident flux on the disc at a given radius R.

Using formulae (2) and (3), the boundary disc radius $R_{\rm bd}$ can be obtained:

$$R_{\rm bd} = \frac{3}{2}\frac{A}{f\eta}\frac{GM}{c^2} = 2.23\cdot 10^{10}\frac{M}{M_\odot}(\frac{f\eta^*}{10^{-5}})^{-1} \text{ cm}, \quad (4)$$

where it has been assumed that $F_{\rm irr}(R)$ / $F_0(R)$ equals A. Here $f\eta^* = f\eta/A$. We note that the ratio $F_{\rm irr}(R)$ to $F_0(R)$ is greater than A if R is larger than $R_{\rm bd}$.

The value of the parameter A depends on the structure of the irradiated atmosphere of the disc and it is different for different lines. Since no precise calculations are available, A should be regarded as a free parameter for each line. Sakhibullin & Shimansky (1996) found from exact LTE calculations of irradiated stellar model atmospheres, that lines of ions are more affected by external X-ray radiation than neutral element lines. The effect of X-ray irradiation on the lines of neutral elements is even lower if departures from LTE are taken into account (Sakhibullin & Shimansky 1995). The results obtained by these authors support our approach here.

The second parameter that characterizes a spectral line is the line temperature, $T_{\rm line}$, determined as the $T_{\rm eff}$ of the stellar model giving the highest equivalent width of the line. As a consequence of the adopted self-irradiation model, it is required that $T_{\rm line}$ is higher than the temperatures of the outer disc and boundary disc radii. These conditions can be re-written by using the usual parameters of accretion discs, $R_{\rm out}$, M, and relative disc luminosity $L/L_{\rm Edd}$:

$$R_{\rm out} > 9.24\cdot 10^{10}(\frac{M}{M_\odot})^{2/3}(\frac{L}{L_{\rm Edd}})^{1/3}(\frac{T_{\rm line}}{5000\text{K}})^{-4/3} \text{ cm} \quad (5)$$

$$\frac{L}{L_{\rm Edd}} < 0.014\frac{M}{M_\odot}(\frac{T_{\rm line}}{5000\text{K}})^4(\frac{f\eta^*}{10^{-5}})^{-3}. \quad (6)$$

The previous conditions allow us to establish which absorption lines might be observed in the spectra of X-ray novae if the accretion disc parameters M, L, $R_{\rm out}$ and $f\eta^*$ were known. Conversely, the values of these parameters may be estimated from the observation of absorption lines in these spectra.

For example, the relation (6) can be rewritten as

$$f\eta^* < 6\cdot 10^{-6}(\frac{M}{M_\odot})^{1/3}(\frac{L}{L_{\rm Edd}})^{-1/3}(\frac{T_{\rm line}}{10000\text{K}})^{4/3}, \quad (7)$$

where the Balmer lines temperature was taken as 10000 K. Since the current estimates of the masses of the compact primaries in X-ray novae lie in the range 1–10 $M_\odot$ and relative luminosities L/L_{Edd} of X-ray novae can be estimated as 0.1–0.01 during outburst decay, the value of the parameter $f\eta^*$ cannot be greater than 10^{-4}–10^{-5} if the Balmer lines have absorption wings as seen in the spectra of GRO J0422+32 and XN Vel 1993 (see references above). We note that direct calculations of $f\eta$ give similar values (Suleimanov 1996). This implies that the parameter A has a value close to 1 or smaller if scattering radiation in a wind or corona were important in the irradiation of the accretion disc.

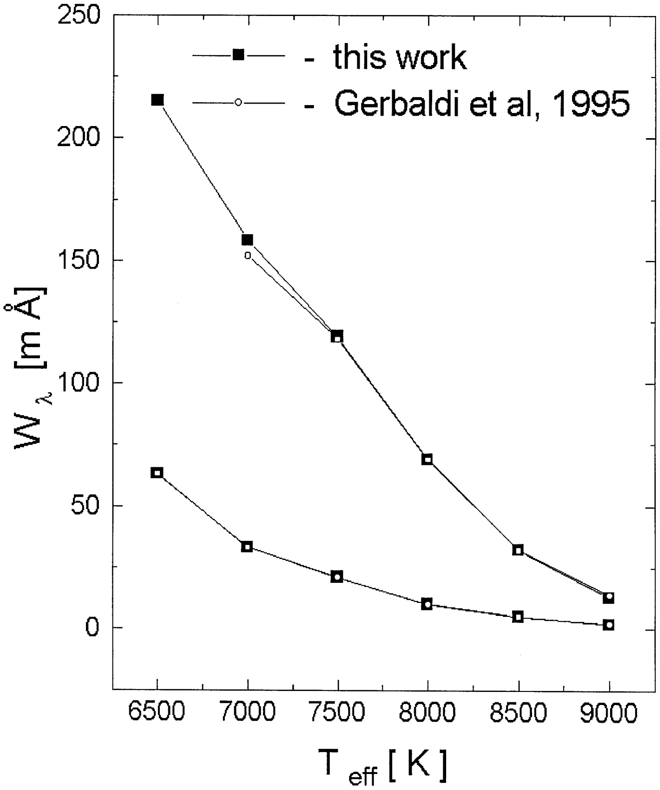

Fig. 1. Comparison of the equivalent width of the Li I λ 6708 Å line computed by us and Gerbaldi et al. (1995) as a function of $T_{\rm eff}$.

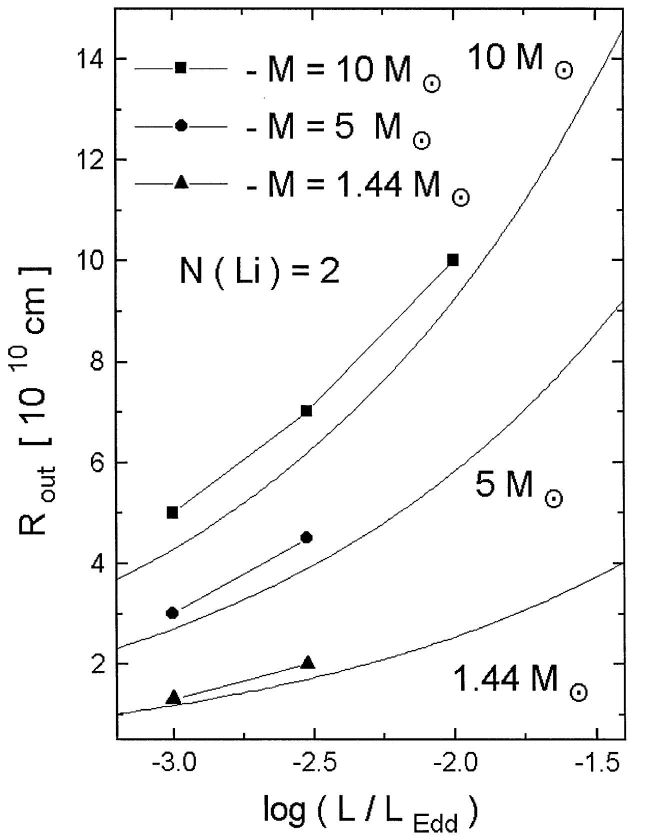

Fig. 2. Dependencies of the smallest outer disc radii, which allows for W_λ of the Li I λ 6708 Å line to be greater than 10 mÅ, on log of relative disc luminosity together with the smallest $R_{\rm out}$ obtained from condition (5) for three central object masses.

3. The Li I λ 6708 line in spectra of self-irradiated accretion discs

According to our assumptions in Sect. 2, the equivalent width, W_λ, of a spectral line in the spectrum of a self-irradiated accretion disc can be determined by the expression

$$W_\lambda = \frac{2\pi \int_{\rm R_{in}}^{R_{\rm bd}} W_\lambda(R) f^c_\lambda(R) R dR}{2\pi \int_{\rm R_{in}}^{\rm R_{out}} f^c_\lambda(R) R dR}, \qquad (8)$$

where W_λ(R) is the equivalent width of the line in the spectrum of the disc ring of radius R and $f^c_\lambda(R)$ is the local continuum flux at the line wavelength. In our case $W_\lambda(R)$ is adopted as the W_λ in the spectrum of a star with the same $T_{\rm eff}$ and log g, as the surface of the accretion disc at radius R. Because the equivalent width of the lithium depends weakly on gravity, an analytical fit of the dependence W_λ from $T_{\rm eff}$ with log g = 4 has been obtained:

$$W_\lambda(T_{\rm eff}) = C \exp(-(T_{\rm eff} - T_0)/t) \text{ mÅ}. \qquad (9)$$

Here $C = -164.3 + 259.34 N({\rm Li}) - 22.63(N({\rm Li}))^2$, $t = 312.5 - 65.8 N({\rm Li}) + 121.0(N({\rm Li}))^2$ and T_0 = 4530 K are the fit parameters, which depend on the Li abundance. This analytical approximation has been found from our LTE calculations of the equivalent widths of the resonance doublet which were performed using Kurucz (1993) stellar model atmospheres. A comparison of our results with those of Gerbaldy et al. (1995) is shown in Fig. 1. The accuracy of the fit is better than 20% in the $T_{\rm eff}$ range 4500 K to 6000 K, and it is of the same order for higher temperatures (up to 9000 K) if $W_\lambda > 70$ mÅ.

A rough estimate of the equivalent width of the Li I line in the spectrum of the accretion disc can be obtained by adopting a black body approximation for the flux in the continuum. We have from Eq. (8)

$$W_\lambda = \frac{C_0 \int_{\rm R_{in}}^{\rm R_{bd}} B_\lambda(T(R)) \exp(-T(R)/t) R dR}{2R^2_{\rm in} hc^{-2/3} (\frac{kT_0}{h})^{8/3} \lambda^{-2.33}}, \qquad (10)$$

where $C_0 = C \exp(-T_0/t)$ and the integral in the denominator has been calculated assuming an infinitely large disc (Lynden-Bell 1969). A first-order approximate integration yields:

$$W_\lambda =$$

$$\frac{2}{3} C_0 \frac{t}{T_{\rm bd}} (\frac{h\nu}{kT_{\rm bd}})^{8/3} \exp(-T_{\rm bd}/t)(\exp(h\nu/kT_{\rm bd}) - 1)^{-1}. \qquad (11)$$

which is accurate to better than 12% as compared with the exact results from Eq. (10). This last expression can be used as a crude estimate of the Li I λ 6708 line equivalent width in spectra of X-ray novae. In order to illustrate this we show in Fig. 2 the dependence of the smallest outer disc radii which allows the

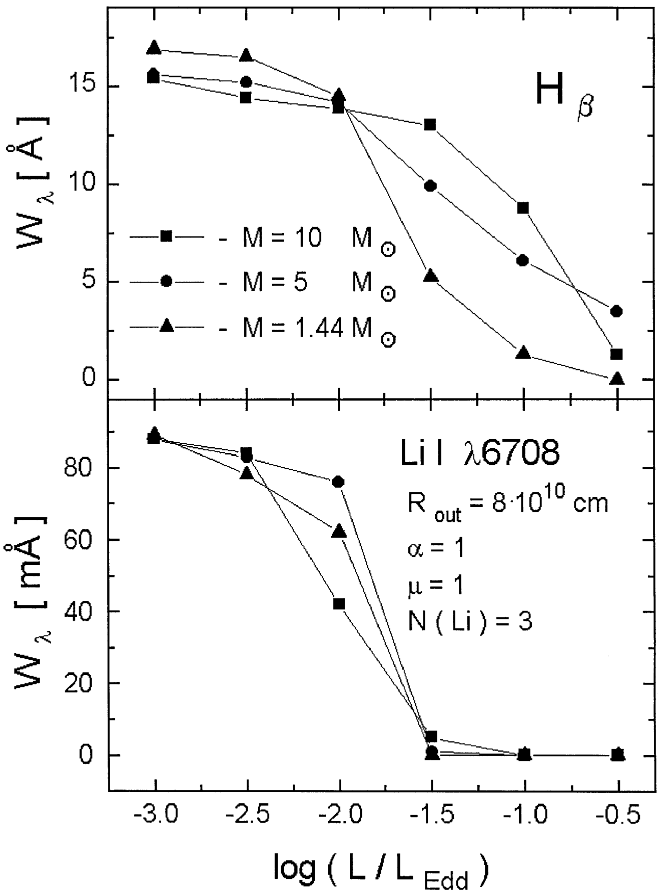

Fig. 3. Equivalent width of the Li I λ 6708 Å and H_β lines vs. log of relative disc luminosity for typical set of disc models (see text), but for different masses of central object.

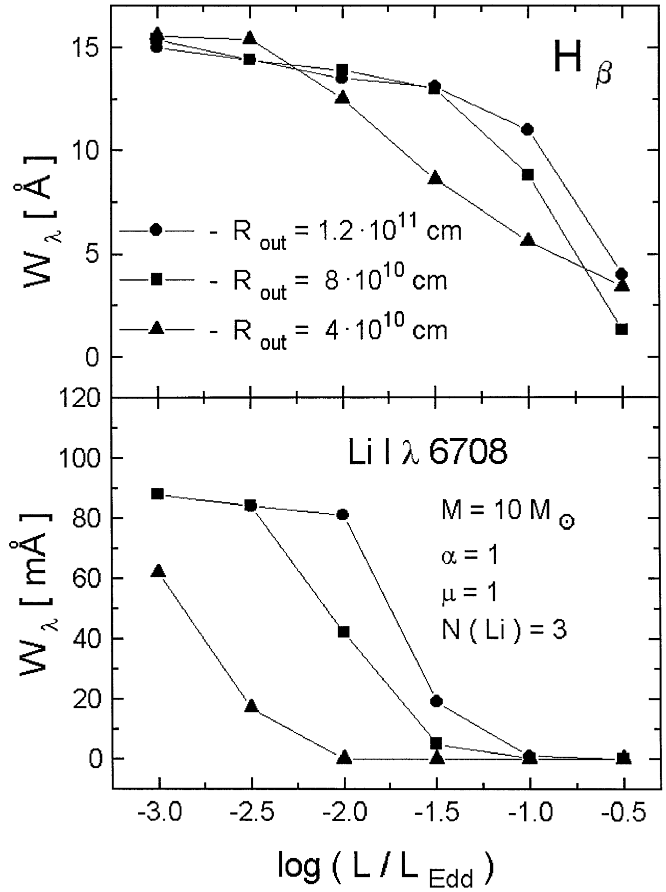

Fig. 4. Equivalent width of the Li I λ 6708 Å and H_β lines vs. log of relative disc luminosity for a typical set of disc models, (see text) and different outer disc radii.

equivalent width of the Li I line to be greater than 10 mÅ versus the relative disc luminosity for three values of the mass of the compact central object. We assume log N(Li) =2, $f\eta^*$ = 10^{-5} and a temperature of 5000 K for the Li I line.

In order to explore the behaviour of the Li I λ 6708 line equivalent widths we have applied Eqs. (10) and (11) in a wide range of accretion parameters and Li abundances. Masses were ranged from 1 to 10 $M_\odot$, $L/L_{\rm Edd}$ from 0.001 to 0.3, $f\eta^*$ from 10^{-5} to 10^{-3} and log N(Li) from 2 to 4. We found that if the disc luminosity is less than 0.03 $L_{\rm Edd}$ and $f\eta^*$ is less than 10^{-4}, then the W_λ of the Li I line is higher than 10 mÅ for log N(Li) greater than 2, and the equivalent width can be as large as 50–100 mÅ for log N(Li)=3. Such absorption lines could be detectable in the spectra of X-ray novae during outburst decay.

It was then decided to conduct a more precise calculation of the equivalent widths of the Li I resonance doublet and H_β in the spectra of the self-irradiated geometrically thin optically thick accretion α-discs around Schwarzschild black holes. The spectra were calculated following the prescriptions given in Sect. 2 and in previous work by Suleimanov (1996) using the computer code STARDISK based on the code ATLAS5 (1970). The value of $f\eta^*(R)$ was calculated assuming A= 1, but only directly impacting X-ray radiation was taken into account. The disc half-thickness $z_0(R)$ was obtained with real opacity and disc structure along the z-coordinate taken into consideration (Suleimanov 1992). In this approach the radiation field was calculated exactly, from the radiative transfer equation, in those rings where $F_{\rm irr}/F_0 < A$ and $T_{\rm eff} < 50000$ K.

The computations were done for a set of reasonable disc model parameters: M=10$M_\odot$, α=1, $R_{\rm in}$ = 9· 10^5 cm, $R_{\rm out}$ = R($T_{\rm out}$ = 4500 K) but no more than 8·10^{10} cm, log N(Li)=3, μ = cos i = 1 and relative disc luminosities in the range 0.1–0.001 Eddington luminosity. One of the parameters of this typical set or the Li abundance was varied whereas the other parameters were kept constant. In Figs. 3–7 the dependence of the W_λ of Li I and H_β lines on the relative disc luminosity are shown for different masses of the primary (Fig. 3), different outer disc radii (Fig.4), Li abundances (Fig. 5), α parameters (Fig. 6) and disc inclinations to the line of sight (Fig. 7).

As it is evident from Figs. 3-7, the Li I resonance line may be observed provided the disc luminosity is less than 0.01 $L_{\rm Edd}$. The equivalent width depends slightly on α and the central object mass, but the larger $R_{\rm out}$ and the Li abundance the greater the W_λ of the Li I line. And, vice versa, the smaller the disc inclination the greater the W_λ of the Li I line. According to our calculations

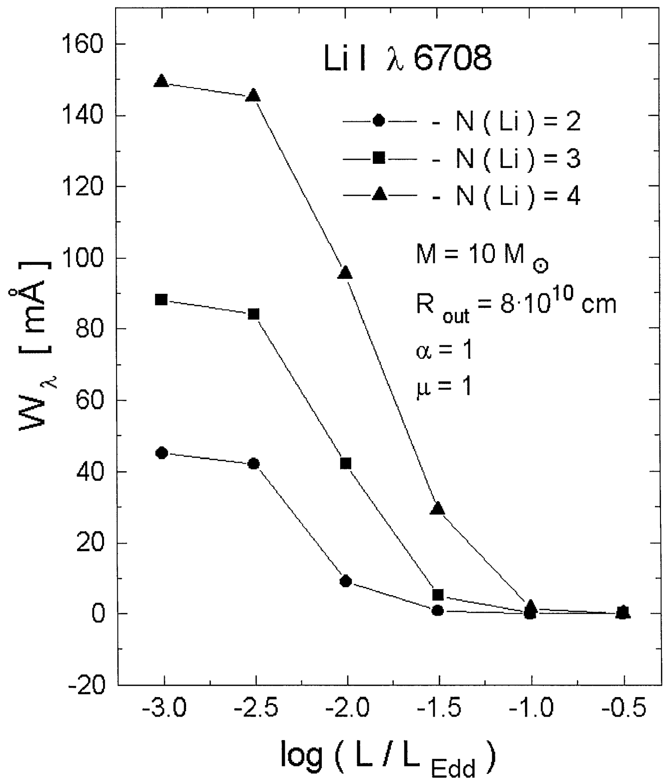

Fig. 5. Equivalent width of the Li I λ 6708 Å and H_β lines vs. log of relative disc luminosity for typical set of disc models (see text), and different Li abundances

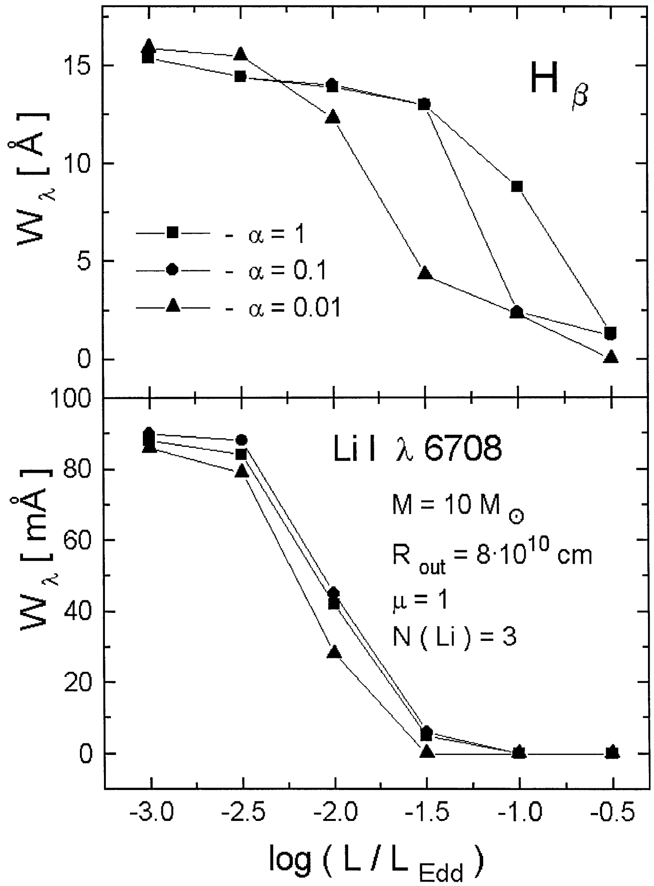

Fig. 6. Equivalent width of the Li I λ 6708 Å and H_β lines vs. log of relative disc luminosity for a typical set of disc models (see text), but for different α parameters

if the equivalent width of H_β is greater than 10 Å the Li I line has $W_\lambda > 20$ mÅ and can be detected.

The exact results seem to be identical to estimate calculations and have close correlation with conditions (5) and (6). This means that conditions (5) and (6) may be used for other lines too.

4. Discussion and conclusions

We have presented here results obtained using a relatively simple method which shows that the Li I resonance doublet may form in absorption in the spectrum of X-ray novae accretion discs. Its strength may allow direct detection with present observational facilities. No any emission component in the calculations of the line has been considered. Such emission components may arise if there is a "chromosphere-like" increase in the temperature distribution of the accretion disc atmosphere caused by irradiation or, in the outer optically thin parts of the disc. The first is important if the disc luminosity is high, $L \sim L_{\rm Edd}$, and the second case plays a dominant role if the disc luminosity is low, $L \sim 0.001 L_{\rm Edd}$. As a consequence, our computations of equivalent widths for the doublet should be considered as upper limits, but they can be close to the real values when the luminosity of the disc has intermediate values $L \sim 0.01\ L_{\rm Edd}$.

In conclusion, the performed exact calculations of the Li I resonance doublet have shown that this line may be strong enough to be detected in the disc spectra of X-ray novae during outburst decay, if $L/L_{\rm Edd} < 0.01$ and if the Li abundance is sufficiently large (log N(Li) $\sim$ 3–4). The expected W_λ can be higher than 100 mÅ in the most favourable cases, when $R_{\rm out}$ of the disc is larger than 10^{11} cm and cos $i \sim 1$. For example, we note that the Li I λ 6708 absorption component may be found in the spectrum of the X-ray nova GRO J0422+32, during the mini-outburst of December 1993. In this spectrum the H_β equivalent width is about 10 Å in absorption. This is possible, of course, if the Li abundance is sufficiently large (log N(Li)>2).

In general, a major difficulty for detection will be the Doppler broadening of the line due to the rotation of the disc. The typical rotational broadening of Balmer lines in the spectra of discs is in the range $\sim$ 500–1000 km/s. Such broadening will be smaller for the Li I line, as it is expected to form near the outer radius of the disc, but it still will make spectroscopic observations of very high S/N ($\sim$ 500 or better) and at least modest spectral dispersion (better than 1Å/pixel) necessary for reaching detections. The new generation of large diameter telescopes may provide the detection of lithium during outburst decay in systems with discs of suitably high inclination angle with respect to the line of sight.

Acknowledgements. We express our sincere thanks to R. L. Kurucz for providing CD-ROMs with new stellar atmoshere models and to T.

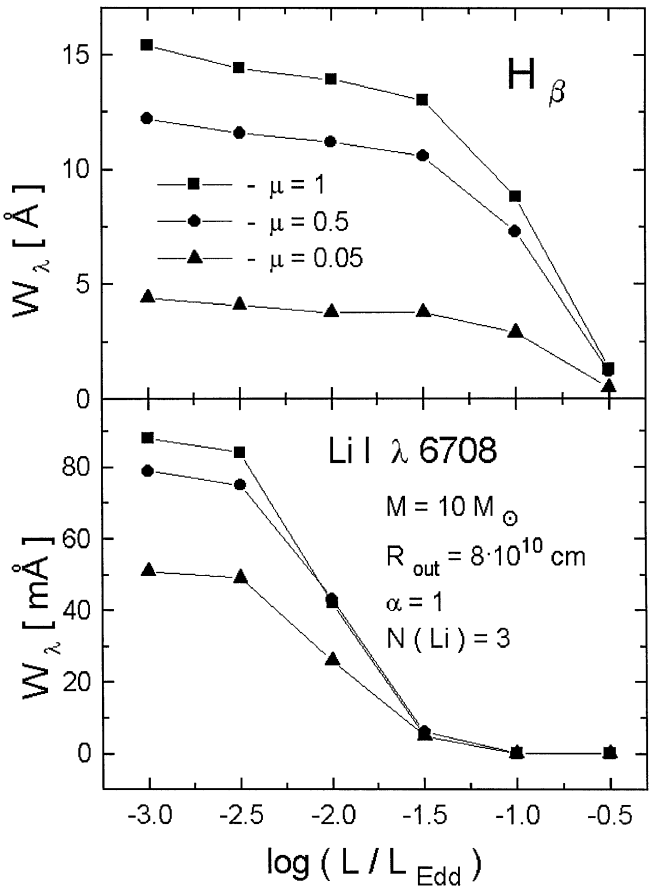

Fig. 7. Equivalent width of the Li I λ 6708 Å and H_β lines vs. log of relative disc luminosity for a typical set of disc models (see text), but for different disc inclination angles

Mahoney for his careful reading of the manuscript. The work of V. Suleimanov has been made possible by a fellowship of the Tomalla Foundation and is carried out under the research programme of the International Center for Fundamental Physics in Moscow. Also his work has been supported by the ESO C&EE Programme (grant A-03-001), the International Science Foundation (grant RHC300), the Russian Basic Research Foundation (grant 94-02-06352-a). Partial financial support for this work was provided by the Spanish DGES project PB95-1132-C02-01.

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