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ON THE LITHIUM CONTENT IN T TAURI-TYPE STARS AND IN COSMIC RAYS

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The resonance doublet of neutral lithium 6708 Li I of considerable intensity was first discovered by Herbig ([1]) in the spectra of two T Tauri-type stars: T Tau and RY Tau. Subsequently Bonsack and Greenstein ([2]), confirming Herbig' s observations, established the presence of this line—moreover a very intense one—in three more stars of the same type: SU Aur, GW Ori, and RW Aur. The amount of lithium in these stars proved to be from 50 to 400 times greater than in the Sun. At present about two dozen T Tauri-type stars are known for which the lithium-to-metals ratio exceeds this ratio for the Sun by two orders of magnitude. At the same time, there is no observational evidence for the presence of lithium in ordinary late-type dwarf stars (later than K0) ([3]). Under these circumstances the fact of the anomalous lithium content in T Tauri stars assumes special significance.

Lithium, as is known, belongs to the class of elements that cannot exist in stellar interiors; at temperatures above $3 \cdot 10^{6\circ}$ lithium rapidly disappears, combining with hydrogen and forming helium. Therefore the presence of lithium in a star' s atmosphere is usually regarded as evidence for the fundamental possibility of the formation of certain elements directly in stellar atmospheres as the result of some nuclear processes. If so, then the abundance of lithium in the atmospheres of T Tauri-type stars should be considered evidence of exceptional activity of nuclear processes in them.

In ([4]) an attempt was made to show that the anomalous lithium content in T Tauri stars is directly related to the phenomenon of continuous emission. The fast electrons responsible for this emission appear in the atmospheres of T Tauri stars as a result of the β-decay of the helium isotope He_2^6, and the lithium isotope Li_3^6 appears as a product of the decay. In contrast to typical flare stars, the process of emission of continuous radiation, and hence the β-decay itself, in T Tauri stars is of a more or less permanent character. Therefore a process of constant accumulation of lithium in their atmospheres will also be inevitable, which, apparently, is what should explain its observed abundance.

However, it can be shown that the real number of lithium atoms in the atmospheres of T Tauri stars is much larger than follows from the observations of Bonsack and others. The point is that the absorption line 6707 Li I belongs to neutral lithium and arises in the transition from the ground state $2s$ to the nearest level $2p$. Meanwhile, in the atmospheres of flare stars lithium should essentially be in a singly ionized state, because the intensity of nonthermal radiation beyond the ionization-frequency limit of lithium (shorter than 2300 Å) during a stellar flare is considerably greater than the intensity of thermal (Planck) radiation beyond the same limit in a normal star of this type or in the Sun. This follows at least from the very fact of the presence of hydrogen emission lines in the spectra of T Tauri stars, which could not be excited without the presence of sufficiently powerful radiation in the short-wavelength region of their spectrum.

On the other hand, it can be shown that the concept of the inverse Compton effect, even at fast-electron energies $E \sim 1.5 \cdot 10^6$ eV, can explain the appearance of emission lines in the spectra of T Tauri stars and similar objects.

In this connection, it is of interest to determine the real content of lithium atoms in the atmospheres of T Tauri stars in comparison with the Sun; for this it is necessary to consider the problem of lithium ionization under the conditions of the atmospheres of these stars. However, lacking observational data on the energy distribution in the continuous spectrum of these stars in the region shorter than 3000 Å, we shall use, as a working hypothesis, the results given in ([5]), i.e., we shall assume that the nonthermal radiation ionizing lithium arises in the atmosphere of the star as a result of the inverse Compton effect.

The starting point is the stationarity condition between the processes of photoionization from the ground state of neutral lithium and the processes of recombination of singly ionized lithium atoms with free electrons. We have

$$n_1 \int_{\nu_0}^{\infty} \chi_{1\nu} \frac{I_\nu(\mu, \tau, T_*)}{h\nu} \, d\nu = n^+ n_e C_{\mathrm{Li}}(T_e), \tag{1}$$

where n_1 and n^+ are the concentrations of neutral and singly ionized lithium atoms; ν_0 is the ionization frequency of neutral lithium; $\chi_{1\nu}$ is the coefficient of continuous absorption from the ground state of neutral lithium; n_e is the concentration of thermal electrons; $C_{\mathrm{Li}}(T_e)$ is the total coefficient of recombination of a lithium ion with an electron; $I_\nu(\mu, \tau, T_*)$ is the intensity of the radiation ionizing lithium, which, for example, in the case of monoenergetic electrons is given by the relation ([5]):

$$I_\nu(\mu, \tau, T_*) = B_\nu(T_*) C_\nu(\mu, \tau, T_*), \tag{2}$$

where $B_\nu(T_*)$ is the Planck function at the effective temperature of the star T_*, and

$$C_\nu(\mu,\tau,T_*) = C_x(\mu,\tau,T_*) = \left(1 + \frac{1}{4\pi}\frac{1}{\mu^4}\frac{e^x - 1}{e^{x/\mu^2} - 1}\tau\right) e^{-\tau}, \tag{3}$$

where $x = h\nu/kT_*$, $\mu = E/mc^2$, and τ is the effective optical thickness of the layer of fast electrons above the photosphere for Thomson scattering processes.

In the case of a normal star or the Sun, the stationarity condition gives, analogously to (1),

$$N_1 \int_{\nu_0}^{\infty} \chi_{1\nu} \frac{B_\nu(T_\odot)}{h\nu}\, d\nu = N^+ N_e C_{\mathrm{Li}}(T_e), \tag{4}$$

where N_1, N^+, and N_e are the same quantities as n_1, n^+, and n_e, but referring to a normal star.

For the coefficient of continuous absorption of lithium $\chi_{1\nu}$, we have ([6]):

$$\chi_{1\nu} = 3.7 \cdot 10^{-18} (\nu_0/\nu)^2 \text{ cm}^2. \tag{5}$$

The recombination coefficient $C_{\mathrm{Li}}(T_e)$ is usually not very sensitive to the electron temperature (at least for hydrogen). Thus, the difference in electron temperatures between the atmosphere of the flare star and the atmosphere of an ordinary star may be ignored. Then from (1) and (4), for the ratio $z_*/z_\odot$, where $z_* = n^+/n_1$ is the degree of ionization of lithium in the atmosphere of the flare star, and $z_\odot = N^+/N_1$ is the same for the Sun, we may write

$$\frac{z_*}{z_\odot} = \frac{N_e}{n_e}\frac{T_*}{T_\odot} e^{h\nu_0/kT_\odot} \int_{x_0}^{\infty} \frac{C_x(\mu,\tau,T_*)}{e^x - 1}\, dx. \tag{6}$$

Sufficiently strong emission lines of hydrogen in the spectra of flare stars, as calculations show, can appear already at $\mu^2 \sim 10$. Taking also $T_* \approx 3000^\circ$K and $\tau \sim 1$, we find from (6)

$$z_*/z_\odot \approx 10^2 N_e/n_e. \tag{7}$$

The greatest uncertainty is the electron concentration n_e in the atmosphere of the flare star. Of course, during a stellar flare n_e increases strongly, above all because of the strong ionization of hydrogen. However, in order of magnitude n_e cannot be greater than the total concentration of hydrogen atoms in the stellar atmosphere (fast electrons will not participate in recombination processes). Therefore, taking $N_1 \sim 10^{12}$ cm^{-3} (for the Sun) and $n_e \leqslant N_e$, we shall have:

$$z_*/z_\odot \gtrsim 100.$$

Thus, the degree of ionization of lithium in the atmospheres of T Tauri stars must be at least 2 orders of magnitude greater than the degree of ionization of lithium in the solar atmosphere. But, as was indicated above, neutral lithium in T Tauri stars is 100 times more abundant than on the Sun. It follows from this that the total number of lithium atoms in the atmospheres of T Tauri stars must be at least $1 \cdot 10^4$ times greater than on the Sun.

This last conclusion may fully characterize the entire unusualness and, at the same time, the exceptional power of the processes taking place in the atmospheres of T Tauri stars and similar objects. The very high lithium content in the atmospheres of these stars may, moreover, serve as an additional argument in favor of the hypothesis of the possibility of β-decay of He^6 in stellar atmospheres and, ultimately, in favor of the concept of fast electrons.

The necessity and importance of the analysis carried out above follow, in particular, from the fact that all lines of singly ionized lithium lie in the far-ultraviolet region (soft X-rays), and therefore in principle ionized lithium cannot be detected in stellar spectra.

The conclusion made above about the high lithium content in stars of the T Tauri type may acquire special interest in connection with the fact of the anomalously high content of light elements, including lithium, in cosmic rays. The ratio Li/H, for example, for the Sun is of order 10^{-11}, whereas for cosmic rays it is of order 10^{-3}. It is usually believed that lithium is a fragment of the spallation of heavy nuclei occurring in the interstellar medium when they encounter protons. This assumption, however, requires the presence of a very considerable quantity of heavy nuclei in the sources of cosmic rays, exceeding their natural abundance by 1–2 orders of magnitude (for details see ([7])).

The possibility is not excluded that the anomalous lithium content in cosmic rays is directly related to the anomalous lithium content in stars of the T Tauri type, and that these stars and similar objects are suppliers of lithium for the interstellar medium. If a stellar flare is in fact caused by the β-decay of He^6 nuclei, then some of the Li^6 nuclei that are fragments of this decay will leave the star and find themselves in interstellar space with an initial energy of order 10^6 eV. At the same time their number is very large; the total number of Li^6 nuclei that can be released during a single very powerful flare is equal to the total number of fast electrons and is of order 10^{45}-10^{46} ([5]). Some of them (what fraction is difficult to say), being accelerated in the magnetic fields of the interstellar medium, enter into the composition of cosmic rays.

Apparently, the considerations set forth above can be checked by analyzing the isotopic composition of lithium in cosmic rays; if the proposed hypothesis is correct, the number of Li^6 nuclei should be greater than the number of Li^7 nuclei, i.e., there should be a ratio inverse to the observed one

on the Sun and in the stars. Unfortunately, we have not been able to find any data on the isotopic composition of cosmic rays. It is therefore of interest to carry out special experiments by installing apparatus on artificial Earth satellites and high-altitude rockets. Of particular interest may be the results of such experiments carried out with respect to the Sun. The nature of chromospheric flares on the Sun and the nature of flares on stars, it seems to us, are one and the same; the difference is only in the scale of the phenomenon. Therefore the very fact of the presence of lithium in the solar component of cosmic rays during solar flares may in itself tell us a great deal.

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Note: Figure translations are in progress. See original paper for figures.