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ON THE STABILITY OF STELLAR ATMOSPHERES

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SUMMARY: The influences of the rotation and radiation on the stability of stellar atmospheres are analysed for the case of hot supergiants and normal MS stars. Also estimated is the expected value of the turbulent acceleration in the atmospheres of the supergiants on the stability margin. In the analysis use is made of the observational material concerning the masses, radii and rotational velocities of stars.

1. INTRODUCTION

The gas outflow from the photosphere and the atmosphere expansion, indicating an unstable mechanical equilibrium of the surface layers, has been observed for many stars. This instability may be due to the individual or joint action of the rotation, energy-transfer mechanisms, magnetic field.

With luminosity increasing in the given spectrum the rotation of the hot stars (O, B and earlier subtypes of A) becomes slower: the most rapid rotation (in general) occurs for hot MS stars, whereas the slowest one in this part of the spectrum is the characteristic of the supergiants (de Jager, 1980; Slettebak, 1970). In the case of the former ones the centrifugal force on the surface is, nevertheless, significantly under the critical value on the average and consequently the rotation influence on the stability of their photospheres cannot be of importance. However, in the case of hot supergiants due to their weak surface gravitation (compared to MS stars of similar masses) the mechanical radiation force can produce an instability of photospheric layers.

Independently of the luminosity class, cool stars (F, G, K) have a slow rotation. Their surface gravitation on the main sequence is stronger than in the case of hot MS stars, but it decreases rapidly with the luminosity increase beyond the main sequence (van Paradijs, 1973; Osborne, 1979; Luck, 1982). Therefore for the case of cool stars the most favourable conditions for arising instability are present in the atmospheres of the supergiants: due to the marginal role of the rotation and radiation it can arise in a strong convection in the subphotospheric layers and develop towards the turbulent motion.

The quantitative evidence concerning turbulence in stars requires reliable atmosphere models and high-resolution spectra. From the survey by Lamers and De Loore (1976) it follows for the microturbulent velocities v_t' in the atmospheres of a few selected (hot and cool) supergiants $v_t'/v_s = 0.5 - 1$, where v_s is the adiabatic sound speed, i.e. $v_t''/v_s = 3 - 4$ for the macroturbulent-motion velocities v_t'' in the case of hot supergiants (I a). On the other hand, the data concerning the measured strength of magnetic field of the supergiants hardly exist at all (de Jager, 1980).

In any case, unstable atmospheres are to be expected above all in the supergiants. Therefore, in this paper on the basis of the available observational material the general stability condition for stellar atmospheres (Sect. 2) is numerically considered for the supergiants (Sect. 3); for the purpose of comparison also given are some ratios for hot MS stars.

2. STABILITY CRITERION

The standard form of the equation for the mechanical-equilibrium at a distance $r \leq R$ from the star centre is

$$\frac{1}{\rho}\frac{\partial P}{\partial r} = -g. \qquad (1)$$

Here R is the star radius, whereas $g(r)$ is the radial acceleration due to the action of gravitational and centrifugal forces:

$$g = g_{\rm grav} - g_{\rm rot}. \qquad (2)$$

The total pressure P consists of the gas ($P_{\rm gas}$), radiative ($P_{\rm rad}$), turbulent ($P_{\rm tur}$) and magnetic-field ($P_{\rm mag}$) components, i. e.

$$P = P_{\rm gas} + P_{\rm rad} + P_{\rm tur} + P_{\rm mag}. \qquad (3)$$

Since for the i-th component of the total pressure it holds

$$g_i = -\frac{1}{\rho}\frac{\partial P_i}{\partial r}, \qquad (4)$$

equation (1) with respect to the force corresponding to the gas pressure in view of (2) and (3) becomes

$$\frac{1}{\rho}\frac{\partial P_{\rm gas}}{\partial r} = -g_{\rm eff} \qquad (5)$$

where

$$g_{\rm eff} = g_{\rm grav} - (g_{\rm rot} + g_{\rm rad} + g_{\rm tur} + g_{\rm mag}). \qquad (6)$$

Condition (5) will be applied to the photospheric layer rotating with velocity $v_{\rm eq}(R)$ in the equatorial plane of a star. If $\mathcal{M}$ and R are the total mass and equatorial radius of the star, it will be

$$g_{\rm grav} = \frac{G\mathcal{M}}{R^2}, \qquad g_{\rm rot} = \frac{v_{\rm eq}^2}{R}. \qquad (7)$$

With the photospheric values for the opacity κ and temperature T_e, in view of (4) also valid

$$g_{\rm rad} = \frac{\sigma}{c}\kappa T_e^4 \qquad (8)$$

where σ and c are the Stefan-Boltzmann constant and vacuum light speed.

The values of the last two efective-acceleration components in (6) depend on the turbulence model and magnetic-field strength B, respectively, with regard to

$$P_{\rm tur} = \alpha\,\rho < v_t^2 >, \qquad P_{\rm mag} = \frac{B^2}{8\pi}. \qquad (9)$$

Here α is a dimensionless parameter whose value (~ 1) depends on the turbulence spectrum varying with the height in the atmosphere, and v_t is the turbulent-motion velocity.

For stable atmospheres, including also those with marginal stability, equation (5) yields the following condition

$$g_{\rm eff} \geq 0. \qquad (10)$$

Since the modelling of $g_{\rm tur}$ and $g_{\rm mag}$ according to (4) and (9) is not unequivocal, the last condition will be referred to the quantity

$$g_{\rm tm} = g_{\rm tur} + g_{\rm mag}.$$

At the same time a new parameter will be introduced

$$\lambda = \frac{v_{\rm eq}}{v_{\rm K}}, \qquad (11)$$

where $v_{\rm K}$ is the Keplerian rotation velocity of the photospheric layer on the equator of the star. In this way according to (10), (6) and (7) one obtains

$$g_{\rm tm} \leq g_{\rm grav}(1 - \lambda^2) - g_{\rm rad}. \qquad (12)$$

3. RESULTS, ANALYSIS AND CONCLUSION

The value of the right-hand side of equation (12) corresponding to the quantity $g_{\rm tm}^{\rm lim}$ will be examined. It depends on several photospheric parameters ($\mathcal{M}$, R, $v_{\rm eq}$, κ, T_e) so that its theoretical dependence on only one of them cannot be derived. In addition, as κ and $v_{\rm eq}$ are unknown within the selected sample of $\mathcal{M}$, R, T_e, it is also impossible to study (from star to star) the observed variations in $g_{\rm tm}^{\rm lim}$. In the case of hot stars with given chemical composition one can only consider (approximatively of course) Tomson's scattering on free electrons, whereas in the case of cool ones $g_{\rm rad}$ can be neglected. However, in both cases the quantity $v_{\rm eq}$ remains unknown for individual stars since the observations yield the value of $v = v_{\rm eq}\sin i$ only. Therefore, in order to use the mean observational values $< v >$, stability condition (12) will be analysed according to the spectral dependence of $< \mathcal{M} >$, $< R >$ and $< v_{\rm eq} >$.

The supergiants and normal MS stars will be considered. The parameter λ for the latter ones will be calculated with the derived values for $< v_{\rm eq} >$ and $< v_{\rm K} >$ according to Fig. 1. Since $g_{\rm rot}/g_{\rm grav} = \lambda^2$ (Fig. 2), it is seen that the rotation of the MS stars on the average has no significant influence on the stability of their atmospheres (the highest value of λ^2, equalling 0.20 – 0.25, occurs at B7 V and A5 V).

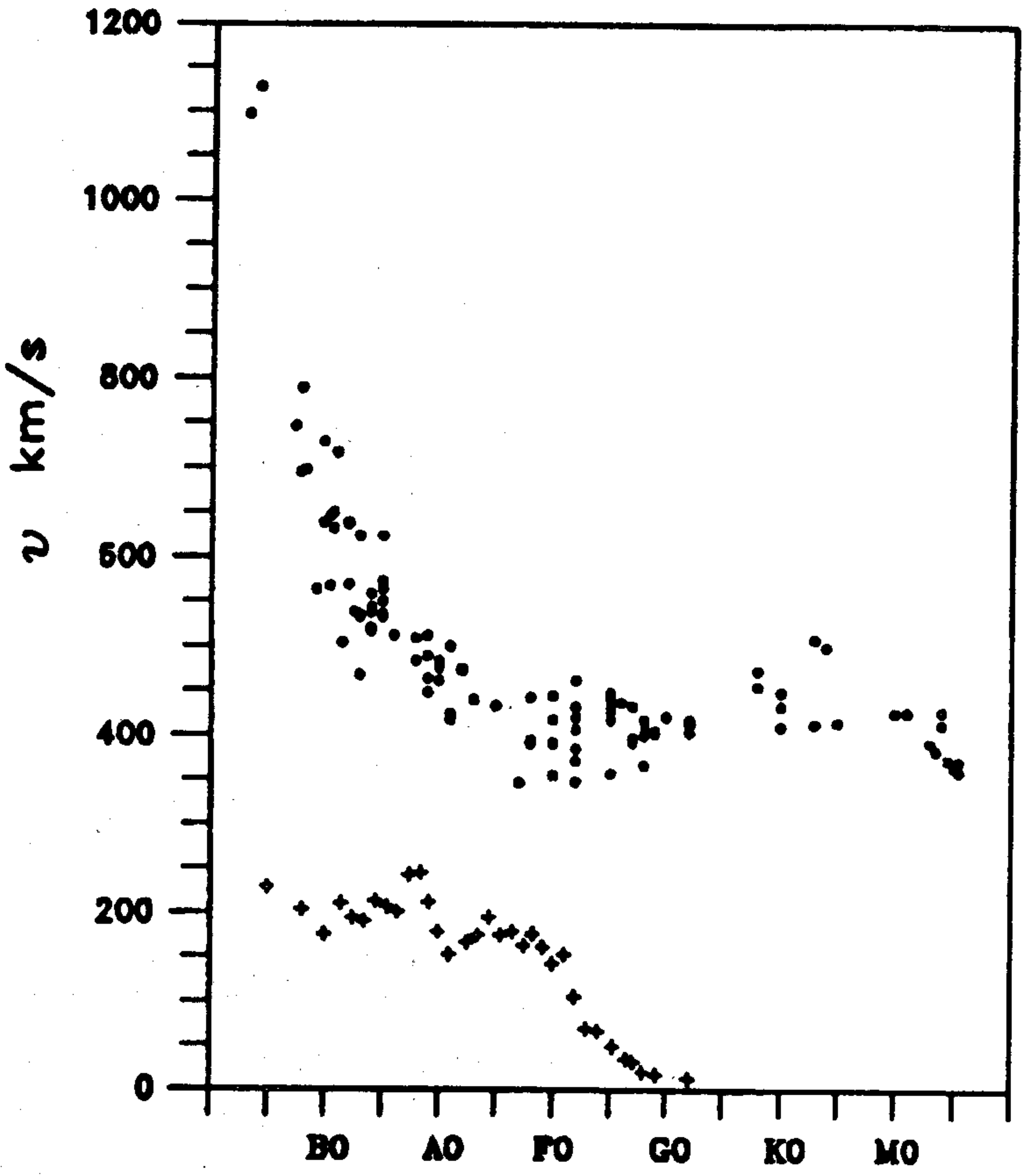

Fig. 1. Rotation velocity on the main sequence
+ – $< v_{\mathrm{eq}} > = (4/\pi) < v >$ (based on $< v > = < v_{\mathrm{eq}} \sin i >$ from Fukuda, 1982).
• – Keplerian rotation velocity $v_{\mathrm{K}}(R)$ with $\mathcal{M}$ and R from Popper, 1980 (including HD 93250 (O3 V) and HD 164794 — 9 Sgr (O4 V) from the survey by de Jager, 1980).

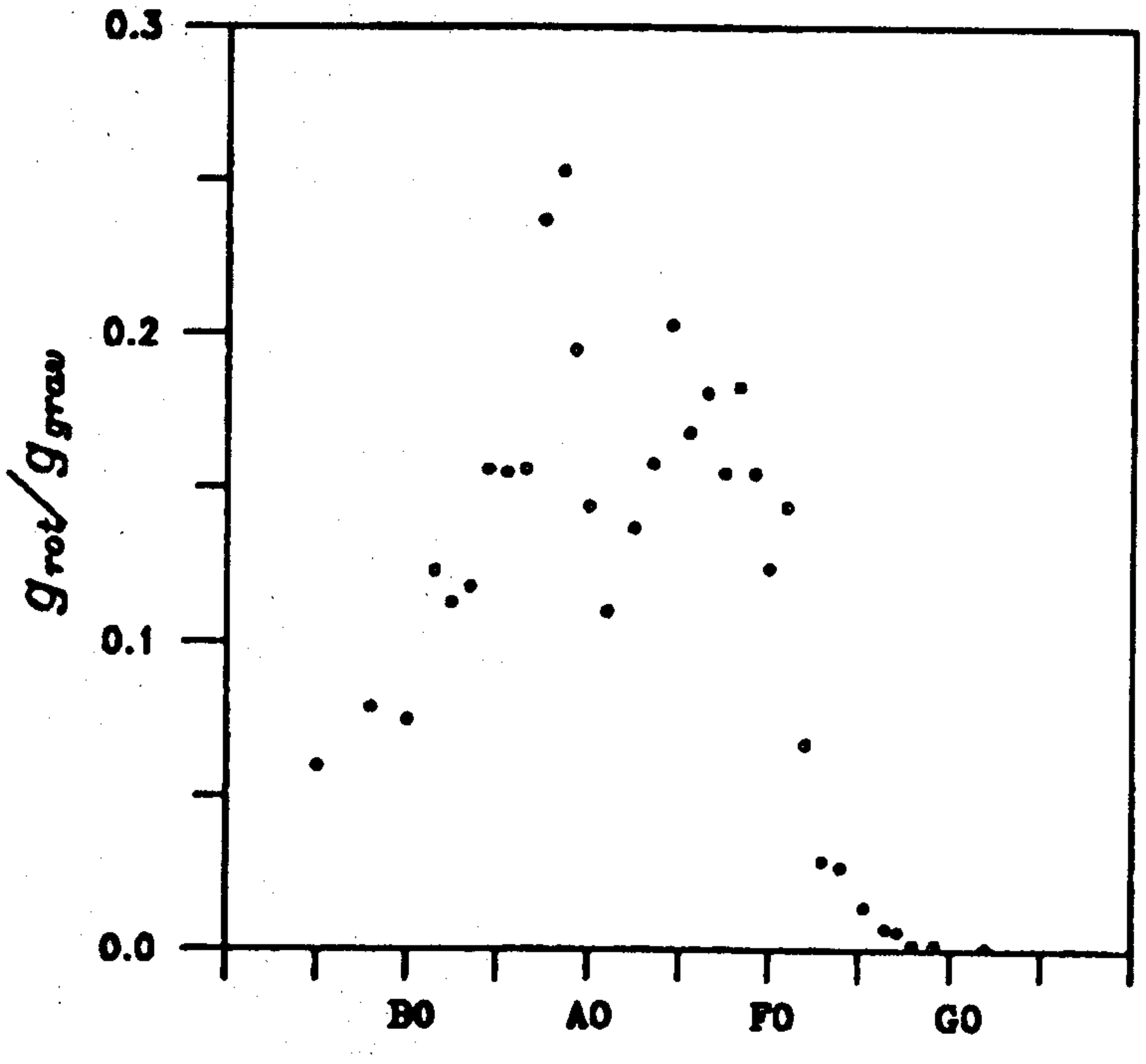

Fig. 2. The ratio centrifugal-to- gravitational force on the surface of MS stars (based on Fig. 1).

The values of λ in the case of the supergiants (luminosity classes Ib–Ia$^+$) are less reliable: the data from different sources indicate a significant dispersion concerning the quantities $\mathcal{M}$ and R for the same stars, the spectral subclasses are insufficiently (and nonuniformly) filled, and the situation concerning the measured $v_{\mathrm{eq}} \sin i$ is similar. For the purpose of the present analysis the hot supergiants from de Jager's (1980) list are chosen where the value of R for some stars is derived from the known amounts for M_b and T_e or from M_v, Sp and T_e. In the case of $< v_{\mathrm{eq}} >$ used are the results for the Ib and Ia/Iab supergiants (Coyne, McLean, 1979), also presented in de Jager (1980), obtained with the data concerning v_{rot} from Boyarchuk, Kopylov (1958).

The atmospheres of hot stars free of turbulence are stable on the average (region above the demarcation line in Fig. 3). This is also valid for the fast-rotating MS stars (O V and B V ones), whereas in the case of the hot supergiants the radiation influence on the atmosphere stability in the absence of turbulence is dominant (the highest value of $\lambda^2 \approx 5\,\%$ is in B1 Ib, whereas the maximum of $g_{\mathrm{rad}}/g_{\mathrm{grav}}$ is about 50 % and it pertains to A Ia$^+$ stars).

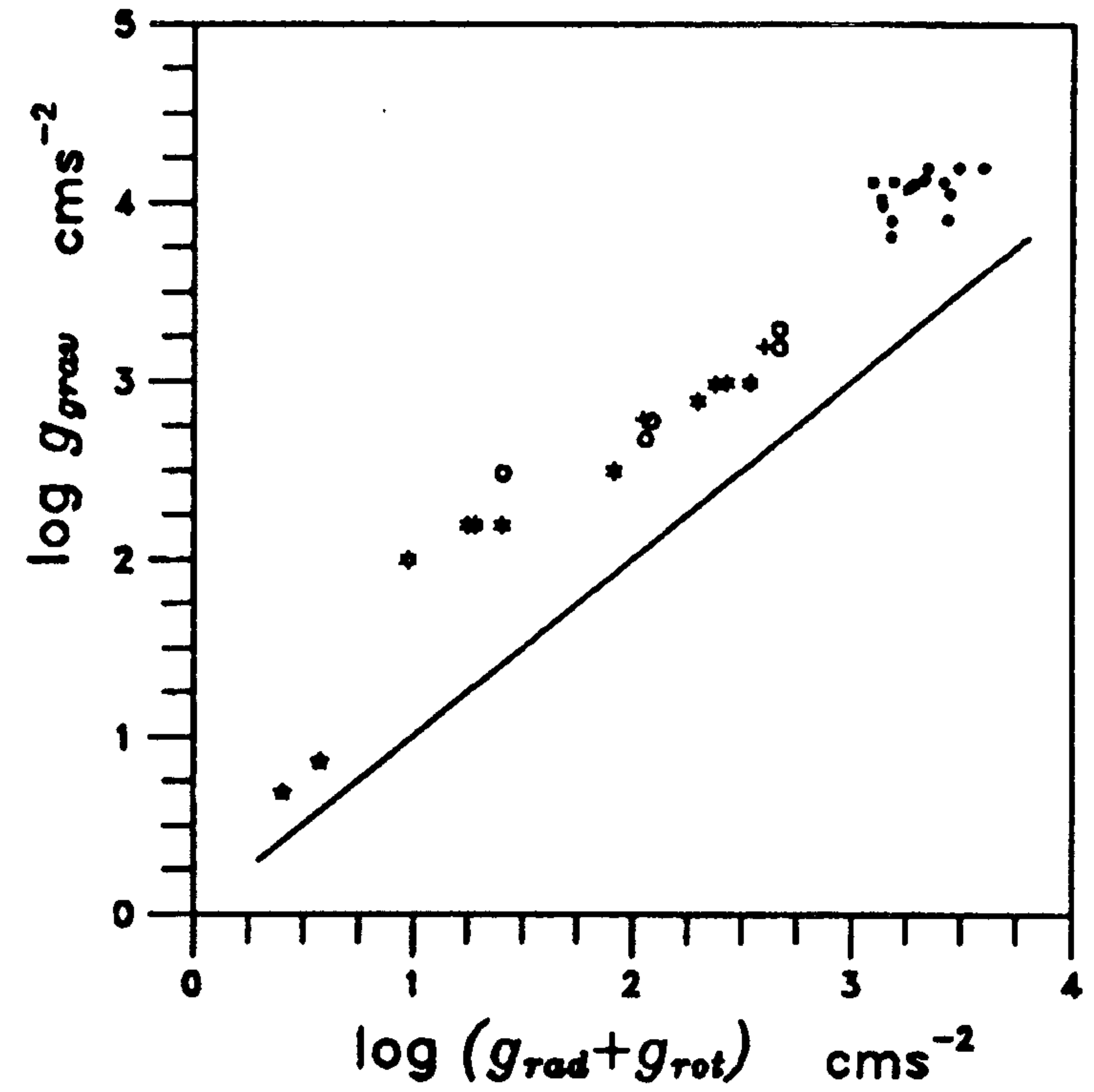

Fig. 3. Stability of hot-stars atmospheres without turbulence. Unstable atmospheres are below the line $g_{\mathrm{grav}} = g_{\mathrm{rot}} + g_{\mathrm{rad}}$.
$\star$ – Ia$^+$, $*$ – Ia, + – Iab, $\circ$ – Ib, • – V.

According to (12) in Fig. 4 is presented the dependence of g_{tm} on T_e for the case of the hot-stars atmospheres with marginal stability ($g_{\mathrm{tm}} = g_{\mathrm{tm}}^{\mathrm{lim}}$). Regarding the turbulence on the main sequence as most likely negligible, the atmospheres of the MS stars are stable (Fig. 3). On the other hand, the theoretically modelled internal structures of post-main-sequence stars indicate an instability occurence within the envelopes of the giants and supergiants. At the same time, though there are difficulties concerning the separation of the influences of rotation and macroturbulence on the width of spectral lines, the observations, as well as the atmosphere models, indicate the presence of the turbulence in the atmospheres of the supergiants (Lamers and De Loore, 1976). Since the magnetic-field strength for the supergiants is probably negligible (de Jager, 1980), the dominant component in g_{tm} is the turbulent acceleration; Fig. 4 for that case indicates significant values for g_{tur} in the unstable atmospheres (region $g_{\mathrm{tm}} > g_{\mathrm{tm}}^{\mathrm{lim}}$).

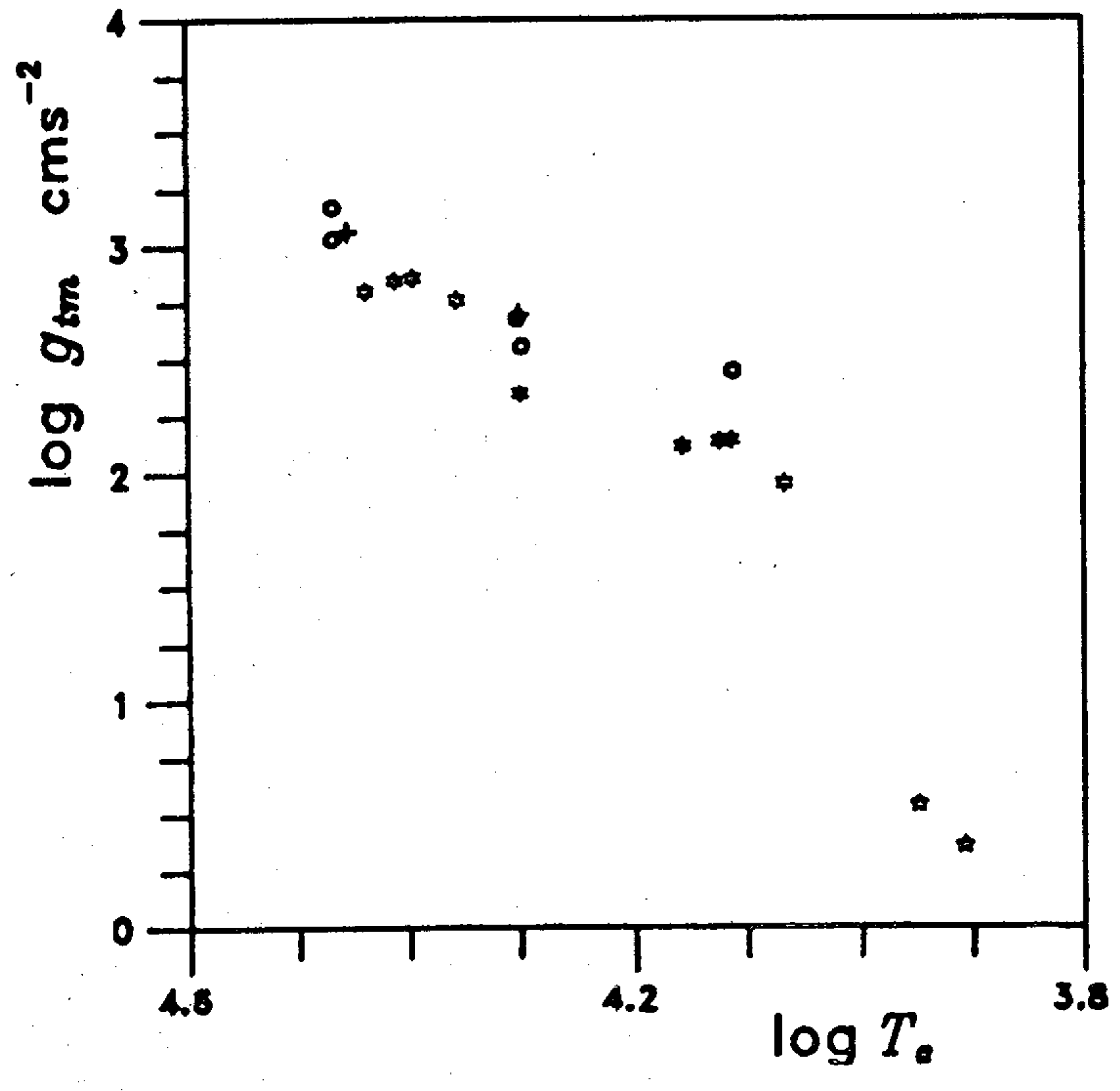

Fig. 4. The value for g_{tm} according to (12) in the atmospheres of hot supergiants on the stability margin.

$\star - \mathrm{Ia}^{+}$, $\ast - \mathrm{Ia}$, $+ - \mathrm{Iab}$, $\circ - \mathrm{Ib}$.

The values for λ^2 and g_{rad} in the case of the cool supergiants are negligible. Due to this criterion (12) yields on the stability margin $g_{\mathrm{tur}} \sim g_{\mathrm{grav}}$ which can be used in the modelling of such atmospheres.

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О СТАБИЛНОСТИ ЗВЕЗДАНИХ АТМОСФЕРА

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Оригинални научни рад

Анализира се утицај ротације и зрачења на стабилност атмосфера топлих суперџинова и нормалних звезда главног низа. Процењује се, такође, очекивана вредност турбулентног убрзања у атмосферама суперџинова на граници стабилности. У анализи се користи посматрачки материјал за масе, радијусе и ротационе брзине звезда.