PRE-MAIN-SEQUENCE STELLAR EVOLUTION*

G.S. Bisnovatyi-Kogan
Space Research Institute, Moscow, USSR

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ABSTRACT

The problems of the stellar evolution to the main sequence are reviewed, taking into account the effects of mass loss, rotation and binarity. Properties of T Tauri stars are discussed which are connected with the recent observations of these stars in ultraviolet and X-ray regions. FU Ori phenomen is considered briefly.

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The foundations of the theory of pre-main sequence evolution have been installed by C. Hayashi in his famous paper, published in 1961. Since then the concepts of "Hayashi track", "Hayashi limit" have been constantly used by the astrophysicists, working on the problems connected with stars.

Here I want to make a review of the mordern state of the theory and to discuss the observational properties of pre-main sequence stars of T Tauri type. These stars have been investigated not only in optical but also in UV and X-ray regions from the satellites. The interpretation of the observations can be made, if we assume that T Tauri stars have a hot corona and chromosphere.

I. EVOLUTIONARY CALCULATIONS

1. Evolutionary tracks without rotation and mass loss

The main features of the quasi-hydrostatic pre-main sequence evolution have been established by Hayashi (1961) (see also Hayashi, Hoshi and Sugimoto, 1962 and Hayashi, 1965). On the early stages of contraction the luminosity L is high, the temperature T inside the star is low, so the noncomplete ionization and high opacity result in the formation of a totaly convective, contracting star. During the contraction L decreases, T increases and for $M > \sim 0.2\ M_\odot$

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the radiative core is formed before the star comes to the main sequence (see fig.1). The relative mass of the radiative core at the beginning of the hydrogen burning increases with increasing the stellar mass. Burning of deuterium leads to increasing the life time of the

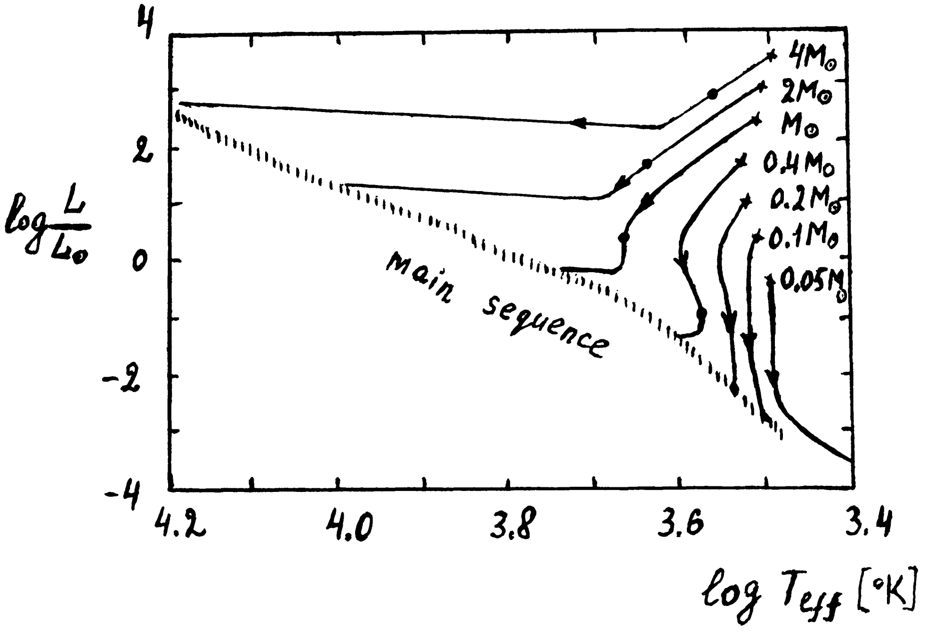

Fig. 1. The evolutionary tracks of pre-main-sequence stars in the stages of quasihydrostatic contraction according to Hayashi (1961, 1965). The crosses denote the initial models,. the circles indicate the ends of the wholly convective stages or the zero-age main-sequence stages.

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star on the pre-main-sequence stage (see calculations of Mazzitelli and Moretti, 1980).

Considerable progress has been made in recent years in the field of the pre-main sequence evolution of massive stars with $M > (3 \div 5)\ M_{\odot}$ (Appenzeller and Tscharnuter, 1974; Larson, 1977). The radiative cores are formed in these stars immediatly after the dynamical collapse at the beginning of the contracting phase. The rate of the core contraction is greater than the rate of the accretion of the matter from the extended envelope. So, the star comes to the point of the hydrogen burning still surrounded by the extended cold envelope. After the beginning of the hydrogen burning the outer envelope may be blown out by radiation and the star completely changes its appearance: on the place of the cold infrared star appears a hot main sequence star. This process may be related to the phenomenon FU Ori (Larson, 1977).

2. Taking into account the mass loss

Kuhi (1964,1966) has shown, that the spectra of T Tauri stars indicate on the mass loss. The rate of the mass loss is evaluated as $(0.3 \div 6)\ 10^{-7}\ M_{\odot}/yr$ and may influence the evolution. The calculations with a simplified version of mass loss

$$\dot{M} = - \alpha \frac{R^3}{M} \qquad (1)$$

have been made by Ezer and Cameron (1969). The parameter α is equal to $3 \cdot 10^{-14}\ M_{\odot}/yr$ for the solar wind and α is between $10^{-11} \div 10^{-8}$ for T.Tauri stars, The calculations have been made for $\alpha = 10^{-10}$, 10^{-9} and $3 \cdot 10^{-9}$. The characteristic results for initial masses $M = 2.93$ and $2.31\ M_{\odot}$ are shown in Fig. 2. Ezer and Cameron (1971) have found that equal age time lines for different mass loss rates lie very close to one another in the HR diagram. So, the large spread of stellar points on HR diagrams of young clusters cannot be explained as a result of variations in mass loss rate. The authors suppose that the spread in the times of formation of the stars in a few million years can explain the spread in the HR diagram.

3. Evolution of rotating pre-main-sequence stars

The angular momentum of the protostars plays an impor-

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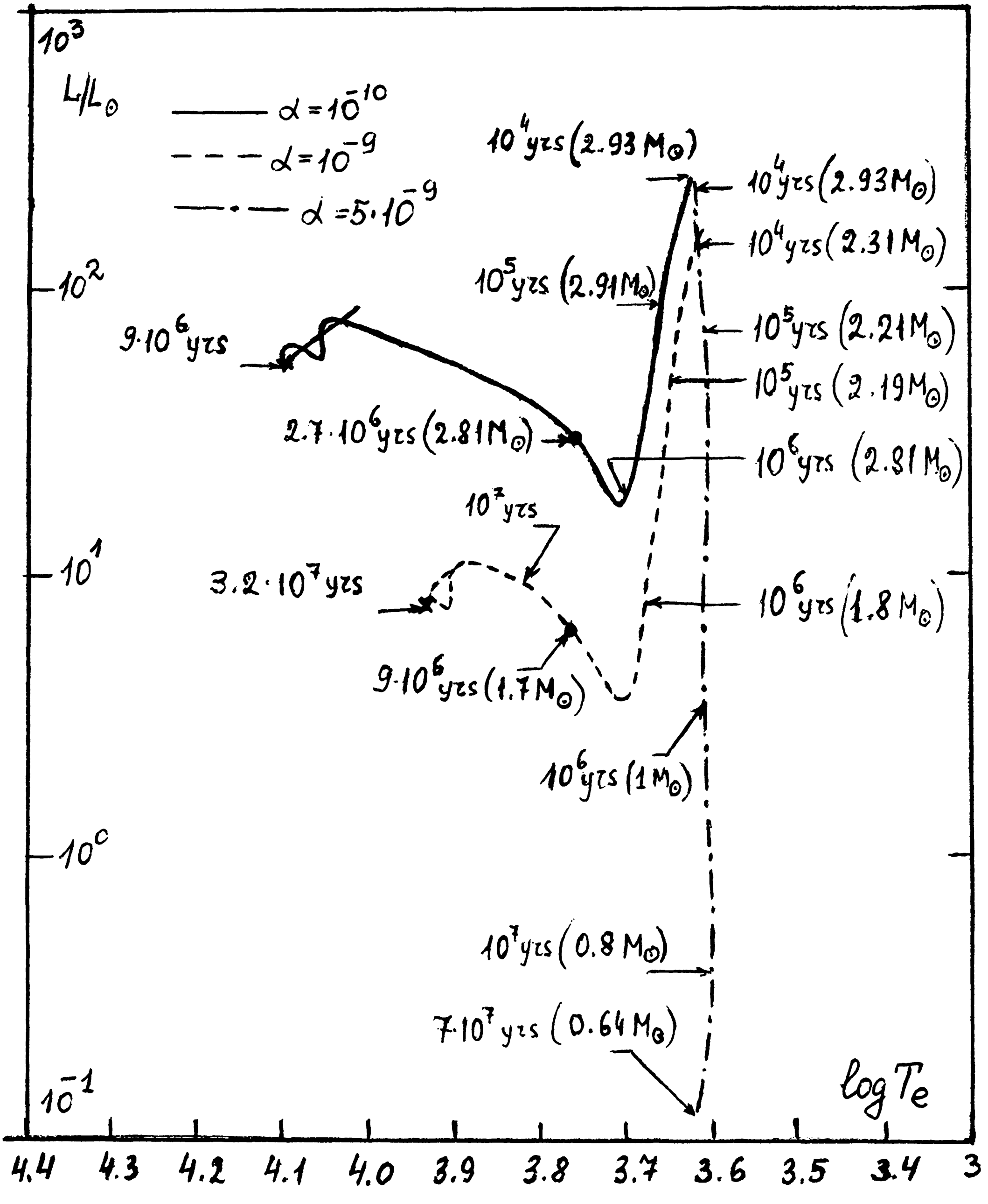

Fig.2. The evolutionary tracks of the deterium burning contracting stars with initial masses 2.93 $M_\odot$ and 2.31 $M_\odot$ and different mass loss rates following Ezer and Cameron (1971). The circles indicate the end of the outer convective zone, crosses - the main sequence. Ages and masses are given on the figure.

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tant role in their evolution, leading to additional mass loss and determining the formation of binaries. The observational detection of the rotation in pre-main sequence stars is rather difficult because of very broad emission linea in T Tauri stars. Herbig (1957) found the value $\langle v \sin i \rangle = 20 \div 65$ km/s, observing four T Tauri stars. The indications on the rapid rotation of T Tauri stars are present in the work of Wilson (1975).

The investigations of the evolution of rapidly rotating stars need complex computations and have been made using some simplifications by Bodenheimer and Ostriker (1970) and Moss (1973). It occurs however, that for totally convective stars which approximate the pre-main sequence stars over considerable interval of their evolution, the evolutionary calculations may be done exactly for arbitrary rotation. This calculations have been made in the papers of Bisnovatyi-Kogan et al. (1977,1979). The main body of the convective star with constant entropy is calculated, using the self-consistent field method in the variant of Blinnikov (1975). The fitting of the envelope to the core is made separately for different points between the pole and equator which permits to find the distribution of the temperature over the star. The results of calculations for $M = 1\ M_\odot$ and $0.5\ M_\odot$ are given in Fig.3. The evolution time up to the main sequence almost doubled compared to the evolution of nonrotating stars. The method of evolutionary calculation gives good accuracy up to the point where the radiative core is not greater than 25% of the stellar mass. The evolution was calculated with the constant angular momentum of the star. During the evolution, the star becomes more flattened. The change of the shape of the star during the evolution is shown in Fig.4. The pre-main-sequence evolution of low-mass stars $M = 0.07\text{-}0.16\ M_\odot$ has been calculated in the papers of Fedorova and Blinnikov (1978); Fedorova (1979). It was shown there, that the minimum mass of a main-sequence star increases from $0.08\ M_\odot$ without rotation up to $0.1\ M_\odot$ for rigid rotation and up to $0.16\ M_\odot$ for differential rotation.

So, the changes in the premain sequence evolution, including moderate mass loss and rotation have a quantitative character. If the limiting rotation reaches in the early stages of contraction then the equatorial mass shedding begins. This process is probably connected with the formation of binary stars and planetary systems.

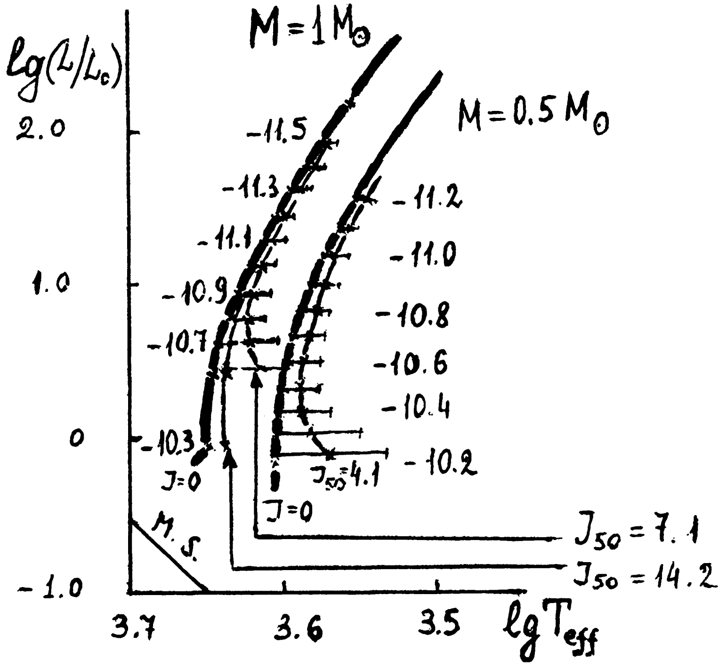

Fig.3. Evolutionary tracks of the contracting stars with masses $0.5M_\odot$ and $1M_\odot$ at different values of the angular momentum J_{50} (in units 10^{50} g cm^2/sec) following the paper of Bisnovatyi-Kogan et al.(1979). The thick lines indicate the results of the calculations by Henyey method for non-rotating stars, crosses - the models calculated by Bisnovatyi-Kogan et al.(1979). The numbers ($\lg\rho_o$ at lgT=3.3 characterize the entropy of the stellar core. The horizontal lines show the spread of the effective temperature along the surface of the star. The main sequence line is indicated below left for X=0.70, Z=0.02. The "entropy" is connected with the age by following relations, where only photospherical luminosity was taken into account.

$\lg\rho_o$	-11.3	-11.0	-10.7	-10.4	-10.2
t(yr)(J =0)	0	$8\ 10^3$	$6\ 10^4$	$3.7\ 10^5$	$1.1\ 10^6$
t(yr)(J_{50}=4)	0	$7.5\ 10^3$	$5.5\ 10^4$	$3\ 10^5$	$8.1\ 10^5$
$\lg\rho_o$	-11.5	-11.2	-10.9	-10.6	-10.3
t(yr)(J =0)	0	$1.5\ 10^4$	$1.1\ 10^5$	$6.5\ 10^5$	$3.6\ 10^6$
t(yr)(J_{50}=7.1)	0	$1.5\ 10^4$	$1.1\ 10^5$	$6.4\ 10^5$	$3.3\ 10^6$
t (yr)(J_{50}=14.2)	0	$1.4\ 10^4$	$9.7\ 10^4$	$3.1\ 10^5$	$5.4\ 10^5$

4. Binaries among the contracting stars

Finding binaries among the contracting stars is also a difficult observational problem because of the broad lines. Only few pairs containing T Tauri stars have been found (Gahm, 1977). Evidently the real number of binaries among these stars is comparable with their number among the main-sequence stars and is about 50% (Martynov, 1979).

It is tempting to connect some unexplained phenomena in pre-main-sequence stars with their hidden binarity (Bisnovatyi-Kogan and Lamzin, 1977a). Let us consider the star V1057 Cyg which suddenly increased its luminosity in 1970. It is known that before the flash the T Tauri type star had been observed in that place (Herbig, 1977). One meets difficulties trying to explain the flash in V1057 Cyg as well as the earlier flash in FU Ori, as a phenomenon on T Tauri stars, The masses of T Tauri stars are essentially less than the evaluated masses of FU Ori, V1057 Cyg after the flash (Petrov, 1977). The difficulties are removed, if to suppose, that the star V1057 Cyg is in the binary system, containing a T Tauri star and another young contracting star of an essentially greater mass. This star undergoes a transition from the hydrodynamical contraction to the state of radiative star close to the main sequence, giving the observed flash, similar to Larson (1977). In this case the T Tauri star still remains in this system and it is worth searching for it in the observations.

II. PROPERTIES OF T TAURI STARS

5. Observational features of T Tauri stars

Optical observations show that T Tauri-type stars have a cool photosphere with $T_{eff} = (3\div5)\cdot10^3$ K and strong UV excesses (Kuhi, 1974). The interpretation of line profiles leads to the conclusion of a mass outflow from these stars with the velocities 150-300 km/sec (Kuhi, 1964, 1965; see also § 2). It is important that the observations of line profiles show deceleration of the outflowing gas (Kuan, 1975). Let us note that the observed mass-outflow velocities are much greater than the characteristic sound velocities, corresponding to the photosphere $V_{se} \lesssim 10$ km/sec.

Simultaneous observations of the star DF Tauri in the region of the line H_α and in UBV show the coherence in their changes (Zaytseva and Lynty, 1976). It was obtained that the variations in H_α emission approximately repeat those in ultraviolet continuum (U-filter) with the time

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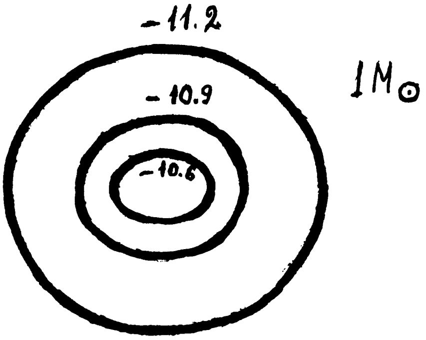

Fig.4. The form of the surface of the contracting star with 1 $M_{\odot}$, J_{50} = 14.2 for different parameters lg ρ_0, connected with the entropy and age of the star (see Fig. 3), following Bisnovatyi-Kogan et al. (1979).

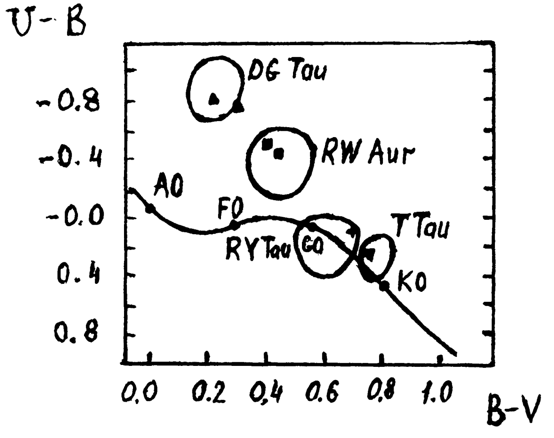

Fig. 5. The position of the theoretical models and observed stars on the two-color diagram from the paper of Bisnovatyi-Kogan and Lamzin (1977). The ovals mark the regions, inside which move the mentioned stars. The line is the main sequence. The same marks correspond to the models with the same stellar radius and different T_c and n_c.

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delay $\sim$ 70 min. There are rapid variations in the line profiles Δt = 10-20 min (Ismailov, 1973; Kolotilov and Zaytseva, 1975) which have been interpreted, as the existance of rather cold ($T \sim 10^4$ K) bulks of the matter moving in different directions. These observations have been explained in the model of a hot outflowing corona, proposed by Bisnovatyi-Kogan and Lamzin (1977b). The model predicted a hot chromospherical layer with $T \sim (5 \div 9) \cdot 10^4$ K for T Tauri stars.

The observations in X-ray and ultraviolet regions permited the chromospheric and coronal emission from these stars to be detected. The indications of the X-ray emission from T Tauri stars have been obtained in the rocket observations of the Orion nebulae (Zwijnenberg, 1976) and ANS satellite (den Boggende et al., 1978). Direct observations of T Tauri stars in Orion nebulae have been done by the Einstein (HEAO-B) Observatory (Ku and Chanan, 1979).

Observations of T Tauri and related stars by the IAU satellite in the region 1150-3100Å lead to the discovery of the chromospheric lines of the ions CIV, SiIV et al., which correspond to the temperature $(5 \div 10) \cdot 10^4$ K (Gahm et al., 1979; Appenzeller et al., 1980). The chromospherical luminosity in this region is equal to 0.3 $L_\odot$ for the star RU Lupi whose optical luminosity is about 2 $L_\odot$ (Gahm et al., 1979).

6. The model of the outflowing corona

All these observations of T Tauri stars are well explained in the model of the hot outflowing corona, proposed by Bisnovatyi-Kogan and Lamzin (1977), based on the optical data. Strong convection in T Tauri stars leads to the formation of a mechanical flux of energy which heats the layers above the photosphere, thus forming a hot corona. The mechanism of the mechanical energy transformation into heat is evidently similar to the mechanism of heating of the solar corona and essentially connected with the magnetic field (Syrovatskii, 1966; Rosner et al., 1978). The characteristic parameters of the corona in T Tauri stars are: $T_c \sim 2 \cdot 10^6$ K, $n_c \sim 10^{11}$ cm^{-3} (at the base of the corona). The characteristic velocity of the matter outflow from the corona is $\sim$ 150 km/sec which is of the order of the observed outflow velocities in T Tauri stars. The thermal emission of the corona may be compatible with/or even greater than, the photospherical optical luminosity. The main flux is in the soft X-ray region, but the ultraviolet emission of the corona may be important for the explanation of

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strong excesses of these stars in "U" filter.

The origin of line emission of the hydrogen and other elements which show the matter outflow, is connected in the model of Bisnovatyi-Kogan and Lamzin (1977) with the relatively cold bulbs of the matter, which are formed in the outflowing hot corona due to the development of thermal instability. These bulks reemit the hard corona radiation in the hydrogen and other optical lines. Such a picture explains the observed time delay in the luminosity rising of the flux in contimuum (first) and H_α line (later) radiation (Zaitseva and Lynty, 1976). This time delay is connected in this model with the time of the development of the thermal instability. The changes in the coronal energy flux may explain the shift of the position of different T Tauri stars in the UBV diagram (Fig. 5). The main prediction of this model is the strong X-ray flux of the coronal origin which may even exceed the optical flux. In such a way the observed X-ray flux from the Orion nebulae may be interpreted as a sum of the emission of T Tauri stars (den Boggende, 1978; Mewe, 1979). It also follows from this model that X-ray emission of the corona leads to the heating of the stellar surface and to the formation of a hot chromospherical layer on its surface with $T = (5 \div 10)\cdot 10^4$ K.

Another model of a T Tauri star, which is based on the accretion instead of the mass outflow, was considered by Ulrich (1976). However observations of absorption variabilities (Zajtseva and Kolotilov, 1974) contradict the accretion model (Lamzin, 1980).

7. The hot chromosphere

Most of the mechanical energy flux goes out into the corona and dissipates there transforming into heat. The hot corona heats the star because of its thermal conductivity and the absorption of its hard thermal radiation. The thermal conductivity is the main source of heating the hot intermediate layer with $T = 5\cdot 10^4 - 10^6$ K on the Sun (Shmeleva and Syrovatskii, 1973). The situation is different for T Tauri stars where the thermal radiation of the corona is much stronger. In these stars the absorption of the X-ray flux from the corona is the main source of heating the intermediate layer. This was shown by Bisnovatyi-Kogan and Lamzin (1980) for the T Tauri-type star RU Lupi as an example.

Application of the thermal conductivity model to explain the radiation of the hot chromosphere ($T \approx 8\cdot 10^4$ K) leads to a very high density at the base of the corona ($\sim 10^{12}$ cm^{-3}) which in turn leads to an unrealistically large coronal luminosity ($> 100\ L_\odot$). Considering the absorption of the coronal energy flux as a mechanism of chromosphere heating it is possible to calculate parameters of the chromosphere and corona, basing on the observed chromospheric energy flux $\sim 0.3\ L_\odot$ (Gahm et al., 1979). The hot chromospheric layer must absorb part of the coronal X-ray flux, falling on the star, so that its average depth for the absorption should be equal to unity. For the known temperature and luminosity of the layer it is possible to calculate the density and thickmess of this layer which are equal to

$n_{ch} \simeq 3 \cdot 10^{12}\ cm^{-3}$, and $h_{ch} = 10$ km, respectively.

Using hydrodynamical equations to describe the outflowing isothermal corona the main coronal parameters have also been calculated for the given coronal temperature $T_c \simeq$ $\simeq 2 \cdot 10^6$ K (Bisnovatyi-Kogan and Lamzinm 1980). It was predicted, that the X-ray luminosity of this star may be of the order of its optical luminosity. The expected fluxes near the Earth are equal to $(1 \div 2) \cdot 10^{-12}$ erg/cm^2 sec in the region 0.2-0.28 KeV, and $(1 \div 5) \cdot 10^{-11}$ erg/cm^2 sec in the regions 0.25-0.5 KeV and 0.5-1.6 KeV taking into account the absorption. This expected fluxes are sufficiently high for detection by the existing X-ray satellites. The two-layer chromosphere must exist on T Tauri stars containing a "cold" layer $T \sim 10^4$ K heated by the dissipation and a "hot" layer $(T \simeq (5 \div 10) \cdot 10^4$ K) heated by the X-ray coronal emission.

8. Some speculations

The existence of mighty chromospheres and coronas on T Tauri type stars as well as on the other stars of late spectral types discovered by "Einstein" arouses a question of the theory of the formation of a strong mechanical energy flux on the stars with connective envelopes. The most optimistic estimates show, that this flux may be of the order of and even greater than the photospherical energy flux. Let us stress the fact that this situation does not contradict the second thermodynamical law. Here it is necessary that in the place where the mechanical energy flux is born, the temperature T_m should be considerably greater than the photospherical temperature. The efficiency of the transformation of the thermal energy into the mechanical form by the star as a thermal machine, does not exceed the value $\eta \lesssim (T_m - T_{ph})/T_m$ which may be more than 0.5.

If the coronal emission of T Tauri type stars is equal to or greater than, the photosphere luminosity it may solve

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in part the contradiction appearing in the determination of the age of young stellar clusters. The age determined by the turning point of the massive stars from the main sequence occurs to be less than the age determined as a time of contraction of low-mass stars. These ages are $(4\div8)\cdot10^8$ and $2\cdot10^9$ years for Hyades; 10^6 and $2\cdot10^7$ years for NGC 2264, respectively (Kraft and Greenstein, 1969). When the total bolometric luminosity is several times greater than the photospherical one, the evolutionary calculations must take it into account, and it would weaken or even remove this contradiction (Bisnovatyi-Kogan et al., 1979).

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DISCUSSION

Massevitch: I should like to summarize briefly several problems left to be solved in pre-main sequence evolution. They are the followings. 1) Precise computations of evolutionary tracks are needed with mass loss, rotation, and magnetic fields taken into account. 2) The effect of rotation on the pre-main sequence evolution of massive stars (the results mentioned in the review are valid only for low mass stars) must be investigated. 3) The "starting model" should be taken directly from the theory of star formation. 4) Discrepancies in the ages obtained for stars in young open clusters must be explained. 5) A theory is needed for the chromospheres and coronae of T Tauri stars. 6) The H-R diagram needs to be interpreted in regions where "very young" and "very old" stars overlap.

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