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On the Luminosity of Spherical Protostars

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Summary. Hydrodynamic model computations have been carried out for a spherically symmetric $1\,M_\odot$ protostar. Compared to similar computations by Larson (1969) we used a different treatment of the accretion shock front. Our computations basically confirm Larsons results and show that Larson's disputed shock jump conditions have little influence on the protostellar models.

Key words: star formation — protostars — YY Orionis stars

I. Introduction

During the past years it has become possible to study the evolution of spherically symmetric protostars by means of hydrodynamic model computations. The most extensive and probably most realistic calculations for low and intermediate mass protostars have been published by Larson (1969, 1972). Most of Larson's basic results have been confirmed by other authors (see e.g. Appenzeller, 1972). But, as noted first by Hayashi and his coworkers (Hayashi, 1970; Narita *et al.*, 1970). Larson's computations seem to contain a systematic error due to a relatively poor approximation of the radiation flow through the accretion shock. Larson's (1972) reply does in our opinion not invalidate Hayashi's criticism: In his computations Larson approximated the radiative energy flux just outside the accretion shock by

$$F=\sigma T_e^4\,. \tag{1}$$

He furthermore assumed $T_e=T_1$ where T_1 is the temperature just below the shock region. Larson based this approximation on the assumption that the shock front emits the radiation flux given by Eq. (1) in the outward as well as in the inward direction. He then argues that in order to get radiative equilibrium in the region below the shock front the local temperature there (T_1) must be of the same order as T_e. During part of the protostellar evolution the shock front is embedded in optically thick layers. The width of the shock front (i.e. the zone of rapid density and pressure increase) is determined by the mean free path of the gas molecules. In a typical protostar this mean free path is much smaller than the mean free path of thermal photons. As a result, the accretion shock should be essentially transparent for the radiation which is emitted on both sides of the shock. Therefore, the inward directed radiation intensity just behind the shock consists of two components: first the flux emitted by the shock front [which may be approximated by Eq. (1)], secondly the radiation emitted by the matter outside the shock front.

At least at the beginning of the main accretion phase the second component is probably more important. If this is the case, T_1 is essentially determined by the radiation from outside the shock front and T_1 may be considerably higher than the "effective temperature of the shock" T_e as defined by Larson. Thus, we agree with Hayashi (1970) that the use of Eq. (1) with $T_e=T_1$ may lead to an overestimate of the protostellar luminosity or to an underestimate of the temperature T_1 below the shock front. In order to study the possible effects of the disputed luminosity jump condition we have repeated the protostellar model computations for $1\,M_\odot$ using exactly the same initial and boundary conditions as Larson for his Case I, but using a different numerical treatment of the accretion shock.

II. Method

The computations were carried out using a modified version of the computer program described in an earlier paper (Appenzeller and Tscharnuter, 1974; hereafter referred to as Paper I). The only major modification was the use of Eulerian (rather than Lagrangian) coordinates in the difference scheme. This change was made after test calculations had shown

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that the use of an Eulerian scheme saved a considerable amount of computing time during the final main accretion phase of the protostellar evolution when the accretion shock is almost stationary in the Eulerian space coordinate.

Like in Paper I the accretion shock was artificially broadened by means of the artificial viscosity method. As a result the density and opacity distribution of our models is incorrect in the vicinity of the shock front. In principle this effect can also introduce serious systematic errors into the protostellar luminosities. However, test computations showed that in the present case changes of the amount of artificial viscosity had no detectable effect on the protostellar luminosity. Thus, in the present case, the artificial viscosity should have no appreciable influence on the luminosity. This behaviour is obviously due to the low opacity and density just above the shock front. As a result these layers are always essentially transparent. Therefore, modifications of the local density distribution have only little influence on the radiation flow through these layers.

III. Numerical Results and Discussion

Most of our results are very similar or identical to those obtained by Larson (1969) for 1 $M_\odot$, Case I.

Small differences in the initial parameters of the hydrostatic cores are probably due to different approximations of the highly uncertain dust opacity values. Significant differences were found for the protostellar luminosity and for the radius and internal structure of the hydrostatic core during the main accretion phase.

The luminosity during this phase, as derived from our computations, is given in Fig. 1. This infrared HR-diagram has been constructed in the same way as Fig. 6 of Paper I. As noted in Paper I, the computed values of T_e depend critically on the highly uncertain dust opacities. Thus, these values are only crude approximations. The luminosities, on the other hand, are not affected by the errors in the dust opacities and should therefore be quite accurate. As shown by Fig. 1, the 1 $M_\odot$ protostar reaches its maximum luminosity during a short-lived luminosity outburst at the beginning of its evolutionary path (at $t=2$ years). This outburst is the result of a luminosity wave which originates in the central region of the protostar, when the infall of matter is suddenly stopped by the formation of the second (final) hydrostatic core. The luminosity outburst occurs when this wave reaches the radiating surface of the protostar. The outburst lasts only a few month. Thus, the probability of observing such an event in a real protostar is extremely small. Except for this initial luminosity outburst our evolutionary path in Fig. 1 is qualitatively similar to the corresponding diagram given by Larson (Larson, 1972; Fig. 12). However, our maximum luminosity (outside the outburst) is only about half as high as Larson's value. During most of the evolutionary phase plotted in Fig. 1 the protostellar luminosity was almost entirely produced by the conversion of mechanical energy of the infalling matter into radiation at the shock front.

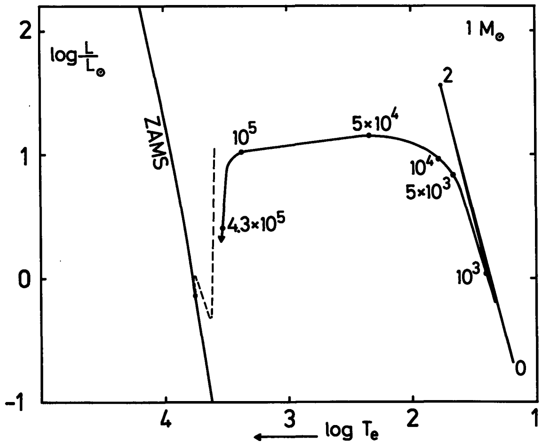

Fig. 1. Evolutionary path of a 1 $M_\odot$ protostar in an infrared HR diagram (solid line). The numbers indicate the time (in years) since the formation of the (final) hydrostatic core. For comparison, the evolutionary path of a conventional fully hydrostatic 1 $M_\odot$ pre-main sequence star is also included (broken line)

Thus the luminosity L was well approximated by

$$L = \dot{M}_c G M_c / R_c \,, \tag{2}$$

where $\dot{M}_c = \dfrac{\partial M_c}{\partial t}$ is the mass accretion rate and R_c and M_c are the core radius and core mass respectively. Only a small fraction of the mechanical energy was converted into internal energy of the matter behind the shock. This small fraction had nevertheless important consequences for the structure of the core. As a result of the energy input, the outer layers of the hydrostatic core were always considerably hotter than the corresponding layers of a star of similar mass and radius in thermal equilibrium. At an age of 4.3×10^5 years (after the formation of the core) this effect resulted in an almost isothermal core structure (cf. Fig. 2). The core radius at this stage was 4.5 $R_\odot$ (which is about twice the radius of Larson's core at the same age). During the later evolution the heat output of the shock decreased rapidly due to the depletion of matter in the envelope. As a result, the temperature gradient in the outer layers increased again and the outer convection zone (which at the stage of Fig. 2 contained only about 1% of the mass) started to grow inwards. Thus, at the end of the evolutionary path, which is plotted in Fig. 1, the internal structure of the hydrostatic core of our protostar approaches the structure of a conventional hydrostatic pre-main sequence star. From the work of von Sengbusch (1968) it is obvious that the remaining differences in the internal structure of the protostellar core and an ordinary pre-main sequence

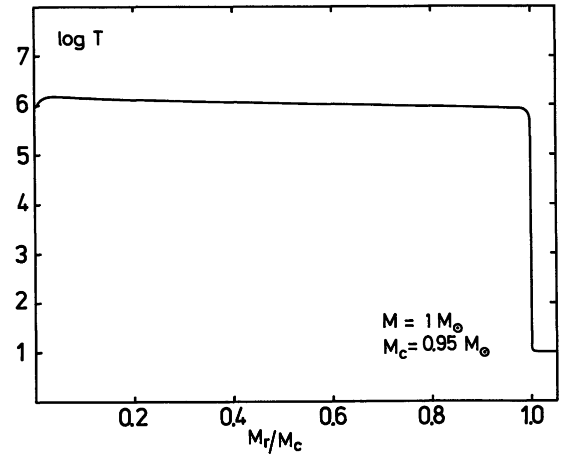

Fig. 2. Temperature distribution in the hydrostatic core of a 1 $M_\odot$ protostellar model after 95% of the total mass has accumulated in the core

model will have little influence on the further evolution towards the main sequence. Also, as a result of the mass depletion the envelope eventually becomes transparent for the radiation of the shock front. A meaningful continuation of the calculation beyond this stage would require a detailed treatment of the radiative transfer in the atmosphere containing the shock front. Such calculations are highly desirable for a comparison with the observations of the YY Ori stars. They are outside the scope of the present paper, however. We therefore stopped the computations at a core age of about 5×10^5 years, after about 97% of the total mass had been accumulated in the hydrostatic core. As pointed out above, the main differences between our results and those obtained by Larson are a lower luminosity of our models during the main accretion phase and a larger core radius and higher entropy of the outer layers of the core during the final protostellar evolutionary stages. These are just the effects predicted by Hayashi (1970). We therefore assume that the differences have been caused by the disputed luminosity jump condition. However, the differences in the observable properties of the protostar are obviously not very large and certainly much smaller than the uncertainties which are introduced into the results by the poorly known initial conditions (cf. Larson, 1969; Narita *et al.*, 1970). As pointed out above, during most of the main accretion phase the luminosity is determined by Eq. (2). Thus, the main effect of Larson's luminosity jump condition seems to be that it underestimates T_1. Apparently this has no serious consequences for the core structure. Thus, in spite of the deviations described above, our calculations confirm Larsons basic results. In particular, our results confirm that, assuming Larson's initial conditions, a 1 $M_\odot$ protostar becomes fully hydrostatic as a low luminosity and only partly convective pre-main sequence star near the lower end of the Hayashi track. As noted by Larson (1969) the computed properties of the protostellar models near the end of the main accretion phase are in good agreement with the observed properties of the so called YY Ori stars (cf. eg. Walker, 1966). The parameters derived from the present computations give an even better fit to these observations. This close agreement may be the best justification for the many uncertain assumptions which enter into the model computations.

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