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Memorie della

Francesco's legacy in primordial star formation studies

K. Omukai

Astronomical Institute, Tohoku University, Aoba, Sendai 980-8578, Japan
e-mail: omukai@astr.tohoku.ac.jp

Abstract. I review here physical and chemical processes in the primordial star formation focusing on Francesco Palla's contributions along with later developments in this field.

Key words. Stars: formation – Stars: Population III – Cosmology: dark ages, reionization, first stars

1. Introduction

According to the standard theory (e.g., Shu, Adams & Lizano 1987), the (low-mass, at least) stars are formed by the following steps: (i) the collapse of dense cores, resulting in the formation of hydrostatic protostars, (ii) the subsequent growth of the protostars by accretion of the ambient matter, and (iii) the accretion termination, e.g. by protostellar feedback, or due to running out of material, which sets the final stellar mass, followed by the quasi-static stellar contraction to the main-sequence stars. Soon after this picture was established in '80s, Francesco Palla and colleagues published pioneering papers, so-called the "trilogy" (Palla, Salpeter & Stahler 1983; Stahler, Palla & Salpeter 1986a,b), and set a firm foundation for the primordial star formation studies. Corresponding to the different stages of star formation above, the first of the series was on (i) the prestellar collapse, the second on (ii) the protostellar accretion evolution, and the third on (iii) the pre-main sequence contraction. Even after those papers, he worked on this topic from time to time and made great achievements.

Although F. Palla also made important contributions to studies on the primordial chemistry before the onset of star formation (see D. Galli's contribution in this volume), here I will focus on the evolution after the dense core formation up to the formation of the main-sequence stars.

2. Pre-stellar collapse and protostar formation

The first stars in the universe are made from the primordial pristine gas, which is composed only of hydrogen, helium and trace amount of light elements synthesized just a few minutes after the Big Bang. The only coolant available in the low-temperature primordial gas is molecular hydrogen. Lacking dust grains, H_2 must be formed in such a circumstance via gas-phase reactions. At low densities, this role is played by the electron-catalyzed H^- channel (Peebles & Dicke 1968; Hirasawa, Aizu & Taketani 1969):

$$H + e \rightarrow H^- + \gamma, \qquad (1)$$

which is followed by

$$H^- + H \rightarrow H_2 + e, \qquad (2)$$

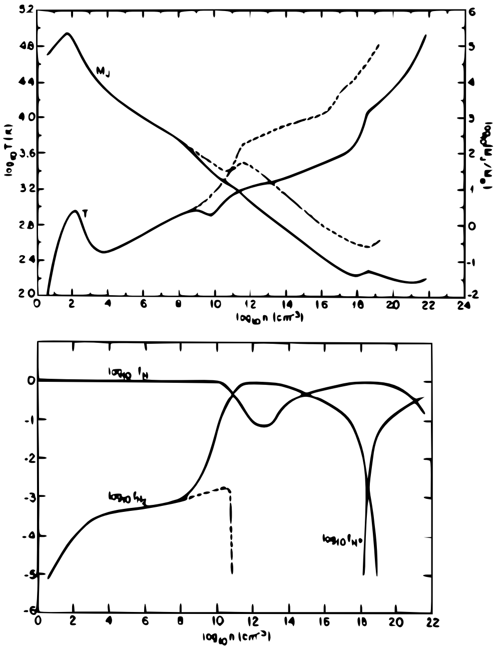

Fig. 1. The impact of the three-body reactions on the pre-stellar collapse. Evolution of (*top*) the temperature and Jeans mass and (*bottom*) chemical fractions of H, H_2 and H^+ as a function of density. The solid (dashed) lines are for cases with (without, respectively) the three-body reactions. Adapted from PSS83. © AAS. Reproduced with permission

and similar proton-catalyzed H_2^+ channel (Saslaw & Zipoy 1967):

$$H + H^+ \rightarrow H_2^+ + \gamma, \quad H_2^+ + H \rightarrow H_2 + H^+. \quad (3)$$

In usual star-forming environments, the former channel is about an order of magnitude more efficient than the latter. At densities $\gtrsim 10^8 \mathrm{cm}^{-3}$, three-body reactions, such as

$$H + H + H \rightarrow H_2 + H \quad (4)$$

and

$$H + H + H_2 \rightarrow H_2 + H_2, \quad (5)$$

become much more important, as was first pointed out by Palla et al. (1983).

Dramatic effects of the three-body reactions are illustrated in Figure 1, adapted from Palla et al. (1983), which shows the thermal (*top*) and chemical (*bottom*) evolution during the pre-stellar collapse. At low densities, the temperature is at several 100K due to the H_2 cooling formed by the H^- channel. The H_2 fraction only reaches $\sim 10^{-3}$ at most. Without the three-body reactions, the temperature goes up to several 10^3K at $\sim 10^{10} \mathrm{cm}^{-3}$ and all the H_2 will be dissociated. On the other hand, with the three-body reactions, all the hydrogen is converted to the molecular form at $\sim 10^{11} \mathrm{cm}^{-3}$. Naturally, subsequent temperature evolution is greatly altered: the temperature increases much more gradually. Thanks to this, the Jeans mass can be as low as $\lesssim 0.1 M_\odot$, so that a small protostar of this size is expected to form.

After Palla et al. (1983), although there were some updates in thermal and chemical processes in the primordial gas, most of them are just minor modifications. One important process missing in Palla et al. (1983) calculation was the cooling by the H_2 collision-induced emission (CIE), i.e., the molecular analogue of free-free emission of ions, which turned out to be important in very high densities ($10^{13} - 10^{16} \mathrm{cm}^{-3}$; Omukai & Nishi 1998). But I've to admit that this process too was already discussed in the Palla et al. (1983) paper, but was concluded unimportant on the basis that H_2 would soon be dissociated just after the density reached the regime where the H_2 CIE is efficient. In reality, however, once its cooling becomes important, the H_2 dissociation is postponed and CIE continues to play a role for some interval. Another ingredient missing is related to the density distribution. The actual hydrodynamical collapse proceeds in a self-similar fashion and a clear core-envelope structure develops. Although Palla et al. (1983) assumed that the cloud is homogeneous with a constant total mass during the collapse in evaluating the optical depth, because of the core-envelope structure, the effective mass of the cloud, which contributes the optical depth, decreases during the collapse. Both of those effects make the cloud to cool more efficiently so that the resultant initial protostellar mass becomes almost as low as the present-day counterpart ($\sim 10^{-2} M_\odot$). Currently, all the evolutionary phases starting from the cosmological initial condition up to formation of the first protostar have been successfully followed by way of the 3D simulations (e.g., Yoshida, Omukai & Hernquist 2008).

3. Growth of protostars by accretion

The end product of the pre-stellar collapse is a tiny protostar with initial mass of $10^{-2} M_{\odot}$, surrounded by a massive envelope of $\sim 1000 M_{\odot}$. After the formation, the protostar grows in mass by accretion of the ambient matter. The accretion rate $\dot{M}$ in this phase can be estimated by the Jeans mass $M_{\rm J}$ divided by the free-fall time $t_{\rm ff}$, $\dot{M} \simeq M_{\rm J}/t_{\rm ff} \sim c_{\rm s}^3/G \propto T^{3/2}$, where $c_{\rm s}$ and T is the sound speed and temperature, respectively, during the pre-stellar collapse. This means that the higher the temperature in the pre-stellar collapse, the higher the accretion rate after the protostar formation. Specifically, in the case of primordial star formation, the rate is $\sim 10^{-3} M_{\odot}$/yr, much higher than that in the contemporary star formation due to much higher temperature of $\sim$ 1000K.

How is the protostellar evolution with such a high accretion rate? Stahler et al. (1986a,b) chose a fiducial accretion rate of $\dot{M}_{\rm fid} = 4.4 \times 10^{-3} M_{\odot}$/yr corresponding to 1700K, which is taken from the pre-stellar collapse result of Palla et al. (1983), and calculated the protostellar accretion evolution by applying the formalism developed by Stahler, Shu & Taam (1980).

Figure 2 (*top panel*) shows the evolution of stellar radius as a function of the protostellar mass, which increases with time. With such a high accretion rate, the protostellar radius becomes much larger than present-day counterpart. Also, even without dust grains, the envelope becomes optically thick to gas opacity, which is due dominantly to the H^- bound-free and free-free absorption, and a photosphere is created within the accretion flow. Its evolution in the HR diagram is shown in the bottom panel of Figure 2. The protostar evolves almost vertically at the effective temperature $T_{\rm eff} \sim$ 5000K, similar to the Hayashi track. But now the star climbs up, rather than going down, unlike the pre-main-sequence stars on the Hayashi track. For technical reasons, Stahler et al. (1986a) stoped the calculation at $10.5 M_{\odot}$.

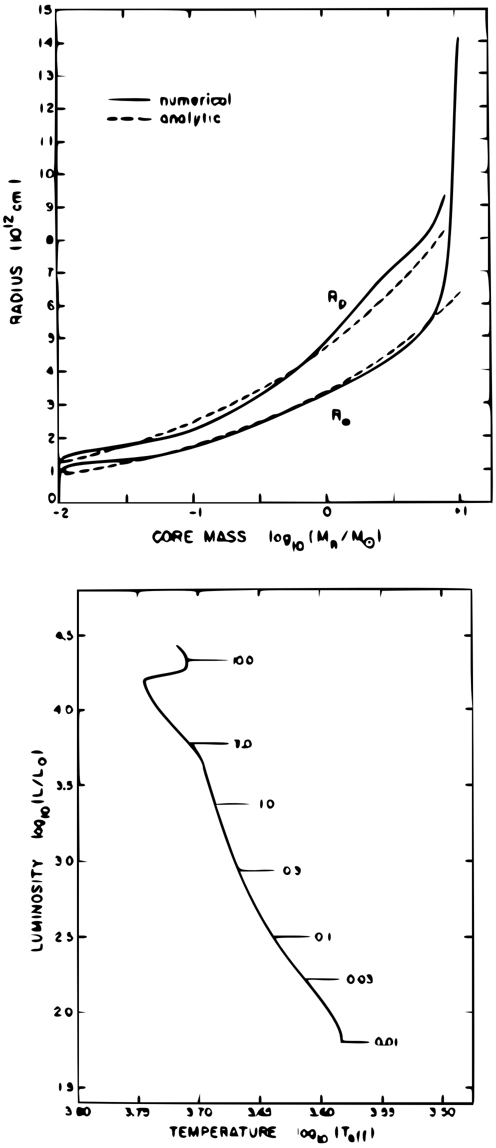

Fig. 2. Protostellar accretion evolution by Stahler et al. (1986a). The star grows from $0.01 M_{\odot}$ to $10.5 M_{\odot}$ at a chosen accretion rate of $4.4 \times 10^{-3} M_{\odot}$/yr. *top*: protostellar (R_*) and photospheric radii ($R_{\rm p}$) as a function of protostellar mass M_*. *bottom*: protostellar evolution in the HR diagram. ©AAS. Reproduced with permission

With ample mass reservoir, the accretion is expected to continue until much later than

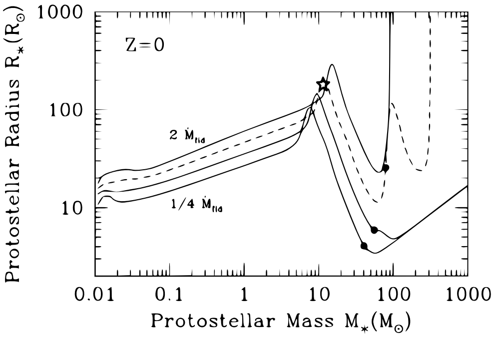

Fig. 3. Evolution of the stellar radii for protostars accreting at four different accretion rates, 2, 1, 1/2 and 1/4 $\dot{M}_{\rm fid}$ (from top to bottom). $\dot{M}_{\rm fid}$ = $4.4 \times 10^{-3} M_\odot/{\rm yr}$ is the value used by Stahler et al. (1986a) and shown by the dashed line. The star symbol shows the final state of Stahler et al. (1986a) calculation. The solid circles indicate the onset of hydrogen nuclear burning. Adapted from Omukai & Palla (2003)

Stahler et al. (1986a) final state. How is the evolution thereafter and when does the star reach the main sequence? I and Francesco worked on this problem when I stayed at Arcetri as a postdoc in 2000-2001 (Omukai & Palla 2001; 2003). The result for the evolution of protostellar radius is shown in Figure 3, where the dashed curve corresponds to the case with the same accretion rate as in Stahler et al. (1986a) and their final state is indicated by the star symbol. Stahler et al. (1986a) speculated that the subsequent phase would be the rapid contraction, which indeed turned out to be the case. Unexpectedly, however, after that phase, the star starts expanding again, then contracts again and inflates violently at the end!

We were puzzled by this behavior at first. It could be understood when we saw the cases with different accretion rates, which are also shown in Figure 3. In all cases, protostars go through the adiabatic accretion ($\lesssim 10 M_\odot$) and Kelvin-Helmholtz contraction ($\lesssim 50 M_\odot$) phases. Evolution after that, however, bifurcates depending on the accretion rate. With low accretion rate, the star reaches the zero-age main-sequence (ZAMS) and the accretion continues unimpeded. On the other hand, at accretion rate higher than a threshold value $> \dot{M}_{\rm crit}$, the star starts inflating when the total luminosity becomes close to the Eddington luminosity. The Eddington limit was the reason for this stellar inflation. The critical accretion rate $\dot{M}_{\rm crit}$ was found to be $4 \times 10^{-3} M_\odot/{\rm yr}$. It is accidentally very close to the value adopted by Stahler et al. (1986a), which causes the complex behavior in the case with this accretion rate.

So, how much is the actual accretion rate? According to the cosmological simulations (e.g., Abel et al. 2002, Yoshida et al. 2008), the accretion rate is initially higher than the critical value and then becomes lower and lower with time. Due to such accretion rate decline, the protostar reaches to a ZAMS star without its radius inflating and the luminosity does not reach the Eddington limit. We expected that the final mass would be only limited by the mass reservoir and a very massive star of a few $100 M_\odot$ would be formed in the spherical accretion case.

Subsequent studies pointed out that in realistic non-spherical accretion cases, the mass of the first stars is set by the stellar radiative feedback, in particular, photoevaporation of accretion disks (McKee & Tan 2008; see also D. Hollenbach's contribution in this volume). With angular momentum, the accretion proceeds through the disk. The UV radiation from the central star ionizes and heats up the disk surface, so that the surface material escapes from the system without reaching the star. For example, in the 2D simulation of Hosokawa et al. (2011), which combines protostellar evolution and radiative hydrodynamical calculations for the accreting envelope, the accretion is halted at $\sim 40 M_\odot$. By repeating the same sort of 2D simulations for a wide range of cosmological initial conditions of minihalos, Hirano et al. (2014, 2015) derived the mass distribution of the first stars, which can be as massive as several $100 M_\odot$ in some cases.

4. What if the high accretion rate maintained?

In usual primordial star formation, the accretion rate falls below the threshold before the star begins inflating. But what if such a high rate is maintained by some mechanism and what happens after the stellar inflation? We originally guessed that the stellar surface continues expanding without limit, which marks the onset of stellar wind. But later, this expectation turned out to be incorrect. Hosokawa, Omukai & Yorke (2012) found that, after the inflation, the stellar expansion saturates at some large radius around 10 au and the star keeps accreting as a "super-giant" protostar without becoming an ordinary main-sequence star. In this mode of star formation, if it indeed happened, people now speculate that a supermassive star would be the outcome (Bromm & Loeb 2003; Omukai, Schneider & Haiman 2008).

Schleicher et al. (2013), in collaboration with F. Palla, discussed analytically the accretion evolution of such super-giant protostars and how massive the star can be before collapsing to a black hole by the post-Newtonian instability. More recent numerical calculation for protostellar evolution including the general relativistic effect demonstrated more directly that the star collapses at a final mass of $10^5 - 10^6 M_\odot$ depending on the mass accretion rate (Umeda et al. 2016). The reader might wonder how such a high value of the accretion rate is realized in nature. Possible, extensively studied scenario is the collapse of a cloud induced by the atomic cooling in strong far-ultraviolet (FUV) fields. If the cloud is massive enough and H_2 formation is quenched by a FUV field, the collapse proceeds only via the atomic cooling almost isothermally at 8000K. In such a case, a very high accretion rate of $0.1 - 1 M_\odot/\mathrm{yr}$ is realized due to the high pre-stellar temperature (Omukai 2001).

How much FUV is needed for the atomic cooling collapse? This threshold value is often called the critical intensity $J_{\rm crit}$, which depends on the UV source's spectral shape (Sugimura, Omukai & Inoue 2014). Thanks to K. Sugimura's effort, I could work with F. Palla again after some interval on this problem (Sugimura et al. 2016; see K. Sugimura's contribution in this volume). Here we calculated $J_{\rm crit}$ as a function of radiation color temperature $T_{\rm rad}$ by considering the H_2^+ channel for H_2 formation. We found that the H^- channel is dominant for $T_{\rm rad} > 7000$K, while, below 7000K, the H_2^+ channel becomes important for lower $T_{\rm rad}$ due to the H^- photodissociation. This result justifies the previous estimate for $J_{\rm crit}$ for young galaxies, which have harder spectra.

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