Formation of the First Stars by Accretion

Kazuyuki Omukai [1] and Francesco Palla [2]

omukai@th.nao.ac.jp; palla@arcetri.astro.it

ABSTRACT

The process of star formation from metal-free gas is investigated by following the evolution of accreting protostars with emphasis on the properties of massive objects. The main aim is to establish the physical processes that determine the upper mass limit of the first stars. Although the consensus is that massive stars were commonly formed in the first cosmic structures, our calculations show that their actual formation depends sensitively on the mass accretion rate and its time variation. Even in the rather idealized case in which star formation is mainly determined by $\dot{M}_{\rm acc}$, the characteristic mass scale of the first stars is rather uncertain. We find that there is a critical mass accretion rate $\dot{M}_{\rm crit} \simeq 4 \times 10^{-3} M_\odot {\rm yr}^{-1}$ that separates solutions with $\dot{M}_{\rm acc} < \dot{M}_{\rm crit}$ in which objects with mass $\gg 100 M_\odot$ can form, provided there is sufficient matter in the parent clouds, from others ($\dot{M}_{\rm acc} > \dot{M}_{\rm crit}$) where the maximum mass limit decreases as $\dot{M}_{\rm acc}$ increases. In the latter case, the protostellar luminosity reaches the Eddington limit before the onset of hydrogen burning at the center via the CN-cycle. This phase is followed by a rapid and dramatic expansion of the radius, possibly leading to reversal of the accretion flow when the stellar mass is about 100 $M_\odot$.

Under a realistic time dependent accretion rate that starts at high values ($\sim 10^{-2} M_\odot$ ${\rm yr}^{-1}$) and decreases rapidly in the high mass regime ($M_* \gtrsim 90 M_\odot$), the evolution follows the case of $\dot{M}_{\rm acc} < \dot{M}_{\rm crit}$ and accretion can continue unimpeded by radiation forces. Thus, the maximum mass is set by consideration of stellar lifetimes rather than by protostellar evolution. In this case, the upper limit can be as high as $\sim 600 M_\odot$.

We consider also the sensitivity of the results to the presence of heavy elements with abundances in the range $Z = 5 \times 10^{-5} Z_\odot$ to $5 \times 10^{-3} Z_\odot$. The main evolutionary features of protostars are similar to those of metal-free objects, except that the value of $\dot{M}_{\rm crit}$ increases for metal-enriched protostars. Since the accretion rate is lower in a slightly polluted environment, the condition $\dot{M}_{\rm acc} < \dot{M}_{\rm crit}$ is expected to be more easily met. We find that for metallicities below $\sim 10^{-2} Z_\odot$, where radiation forces onto dust grains in the flow are negligible, a slightly metal-rich gas favors continued accretion and the formation of very massive stars.

REFERENCES

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[1]Division of Theoretical Astrophysics, National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan

[2]INAF–Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy