Gamma-Ray Bursts from First Stars and Ultra-Long Gamma-Ray Bursts

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Abstract

Gamma-ray bursts (GRBs) are one of the brightest explosions in the Universe. Among them, long GRBs (LGRBs) are believed to be originated from the death of massive stars, or stripped-envelope Wolf-Rayet (W-R) stars, since Type Ic supernovae (SNe) accompany some LGRBs and the explosion sites of LGRBs concentrate on the actively star forming regions of the host galaxies. So far, 5 LGRBs have been detected at redshifts of $z \gtrsim 6$, and they may be a good probe of the early Universe. The current observational frontier of high-z objects is at $z \sim 8$, and various observational missions are now planned at various wavelengths to search the earlier Universe. At $z > 10$, first stars, or Population III (Pop III) stars may be the dominant population and have some impacts on cosmic evolution through radiative, mechanical, and chemical feedback. Since primordial clouds are deficient in metals and dusts which are efficient coolants in the present-day molecular clouds, they owe their cooling to molecular hydrogen (H_2) that is a relatively inefficient coolant. This results in the formation of more massive molecular clouds and more massive stars compared to the present-day counterparts. Recent numerical simulations show that Pop III stars are as massive as 10-1000 $M_\odot$.

Pop III star formation is considered to start typically from $z \sim 30$ and to continue until as low redshift as $z \sim 6$ in the metal-free pockets of the early galaxies. At $z \lesssim 10$, Pop III stars could be formed from primordial clouds that receive radiative or mechanical feedback from the preexisting stars. For example, in primordial clouds with the elevated ionization degree like in relic HII regions which are left after the death of the central Pop III star, hydrogen deuteride (HD)

cooling, in addition to H_2, can be efficient and it can change the evolution of the contracting clouds so as to form less-massive Pop III stars. Thus, HD can have some impacts on the IMF and SFR of Pop III stars. In this thesis, in order to understand the role of HD in primordial clouds, we study how the thermal evolution of a primordial cloud changes in the presence both of the external far-ultraviolet (FUV) field and the cosmic ray (CR) injection. It has been considered that HD is vulnerable to such a weak FUV field as 1% of the background level predicted theoretically at $z \sim 10$. We find, however, that HD could generally be important in primordial star formation, since CR injection can counteract the negative feedback from the background FUV field by elevating the ionization degree through collisional ionization.

Since Pop III stars are considered to be as massive as 10-1000 $M_{\odot}$, they can be the progenitors of LGRBs, called Population III GRBs (Pop III GRBs). Their detection in the near future will provide us rich information about primordial star formation. According to the collapsar scenario of LGRBs, the relativistic jet launched from a central engine should successfully break out of the progenitor envelope and contribute to the prompt γ-ray emission. Naively, this may look problematic in considering Pop III GRBs. Some studies suggest that Pop III stars tend to suffer from little mass loss and evolve as blue supergiant (BSG) stars with massive hydrogen envelopes until the pre-collapse stage, owing to their low-opacity envelopes. Since the plausible progenitors of local LGRBs are stripped-envelope W-R stars, they may be compact enough to be free from this problem. In this thesis, however, we find the successful jet breakouts for less-massive Pop III stars of 30-90 $M_{\odot}$, and then discuss the observational characteristics of Pop III GRBs and their detectability with future satellite missions. We find that Pop III GRBs could have ultra-long durations of $\sim 10^5$ s and are less luminous $\sim 5 \times 10^{50}$ erg s^{-1}, because of the massive hydrogen envelope. Assuming the empirical $E_{\rm p}$-$L_{\rm p}$ (or $E_{\rm p}$-$E_{\gamma,\rm iso}$) correlation for Pop III GRBs, we discuss that Pop III GRBs might be detectable up to $z \sim 19$ (or $z \sim 9$) as ultra-long X-ray flashes (or X-ray rich GRBs) by *Lobster* (or *EXIST*).

Interestingly, some LGRBs are found to show such long lasting prompt emissions as $\sim 10^4$ s and are called ultra-long GRBs (ULGRBs): GRB 101225A, GRB 111209A, and GRB 121027A. Moreover, a bump feature in the optical-IR light curves has been confirmed around $\sim$ 10-50 days after the representative ULGRB, GRB 111209A.

It may reflect an underlying SN component, which is as luminous as a superluminous SN (SLSN) and be a unique feature of ULGRBs. In this thesis, we focus on the BSG collapsar scenario and examine it with the SLSN-like bump. Before the jet breakout, the energy injected into the jet is thrown and stored into the cocoon surrounding the jet. Huger energy will be stored into the cocoon in the BSG collapsar than in the W-R one, since it takes longer time for the jet breakout. We consider the emission from a non-relativistic cocoon fireball that expands outside the progenitor like a canonical SN ejecta, and find that it consistently reproduces the SLSN-like bump of the ULGRB. The above discussion might be applicable to Pop III progenitors, so that some Pop III GRBs might be detected as ULGRBs with accompanying SLSN components.