論文内容の要旨

論文題目

Radiative Transfer, Hydrodynamics, and Nucleosynthesis in Core-Collapse Supernovae

(重力崩壊型超新星の輻射輸送、流体力学、元素合成)

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In this thesis, we explore the nature of supernova (SN) explosions and their contributions to the chemical evolution and elucidate the relation between the properties of SNe and the stars formed in early universe.

I. Properties of supernovae

We unravel the properties of SNe with radiative transfer calculations. In this thesis, we focus on two interesting SNe: (1) a putative SN in the afterglow of X-ray flash (XRF) 030723. XRF 030723 is one of the first XRFs [an analogical events of γ-ray bursts (GRBs) but emitting the radiation in X-ray bands] showing a bump in the optical light curve (LC) of the afterglow, which has been interpreted as a signature of a SN. (2) SN 2005bf that was classified as a Type Ic SN initially but transited to a Type Ib SN later due to the development of He lines. Accordingly, SN 2005bf is implied to locate between Type Ib and Ic SNe. Interpreting their properties provides us new insights on the nature of SNe and GRBs. Further, the accumulation of the properties of SNe and GRBs can constrain the explosion mechanism of SNe, the SN nucleosynthesis, and the progenitor stars of SNe and GRBs observationally.

Putative SN in the afterglow of XRF 030723

We modeled the LC of the putative SN after subtracting the afterglow component from the observed optical LC of the XRF counterpart. Although a poor signal-to-noise (S/N) ratio of the spectrum prevents detailed spectrum modeling, we constrain the relation between the ejecta mass and the kinetic energy of the putative SN: M_{ej}~1-6$M_{\odot}$ and E=1-50x10^{51} ergs. Further, the mass of synthesized ^{56}Ni is M(^{56}Ni)~0.01-0.3$M_{\odot}$ for the redshift range z~0.3-1 inferred from the undetection of the host galaxy and the lack of Lyα absorption.

We attempt to give further constraints on the SN properties. If the relation among M(^{56}Ni), E, and M_{ej} established from models of various Type Ic SNe also holds for the putative SN in XRF 030723, the ejecta mass is constrained to be M_{ej}~1-3$M_{\odot}$ and the kinetic energy E=1x10^{52} ergs. We suggest that the progenitor was a star with M_{ms}~14-25 $M_{\odot}$, being smaller than the progenitors of GRB-associated SNe.

SN 2005bf

SN 2005bf showed unique features: the LC had two maxima, declined rapidly after the second maximum, and strengthening He lines whose velocity increased with time.

We presented a model reproducing the LC and the spectra well. The result of modeling indicates that the SN should have a double-peaked ^{56}Ni distribution and that γ-ray should escape from the SN ejecta more effectively than in normal SNe. The SN has massive ejecta (~6-7 $M_{\odot}$) and normal kinetic energy (~1.0-1.5x10^{51} ergs). The progenitor was likely a WN star of main-sequence mass M_{ms}~25-30$M_{\odot}$. To realize high peak bolometric luminosity (~5x10^{42} erg s^{-1}) with an energy release from the ^{56}Ni decay, a large ^{56}Ni mass (~0.32 $M_{\odot}$) is required. Since large amount of ¥Nifs¥ was required in spite of the small explosion energy, the compact remnant should be as small as M_{rem}~1.4 $M_{\odot}$, i.e., a neutron star.

II. Chemical evolution in the early universe

SN nucleosynthesis contributes the chemical evolution of the universe. The contribution of an individual SN is particularly important in the early universe because the interstellar gas was not mixed well. Therefore, the stars formed in the early universe possess information on nucleosynthesis in an individual SN.

The stars with low Fe abundances (metal-poor stars) are observed in the Galactic halo and considered as the stars formed in the early universe. We perform one- and two-dimensional hydrodynamical and nucleosynthesis calculations and compare the abundance patterns of the yields with those of the metal-poor stars. Accordingly, we reveal the properties of SNe in the early universe from the abundances of the metal-poor stars and compare their properties with the recent-days SNe.

Main-sequence mass and explosion energy

We perform one-dimensional hydrodynamical and nucleosynthesis calculations of core-collapse SNe and hypernovae (HNe) of Pop III stars for the main-sequence mass of $M_{ms}=13\text{-}50M_\odot$ and the explosion energy of $E=1\text{-}40\times10^{51}$ ergs. Adopting the empirical relation for the present SNe which a larger amount of Fe is ejected by more massive HNe, we reveal the followings:

(1) HN yields applied the mixing-fallback model reproduce the abundance pattern of extremely metal-poor (EMP) stars (-4<[Fe/H]<-3), while the abundance pattern of very metal-poor (VMP) stars (-3<[Fe/H]<-2) is reproduced by the normal SN yields or the yields integrated over the Salpeter initial mass function.

(2) The trends of abundance ratios [X/Fe] against [Fe/H] with small dispersions for the EMP stars can be reproduced by a sequence of models with the various combinations of M_{ms} and E. We propose that the trends of abundance ratios indicate an ``inhomogeneous'' chemical evolution in the early universe at [Fe/H]<-3, instead of the homogeneous mixing in the interstellar medium.

(3) We examine how the distributions of the electron mole fraction Y_e and the density in the presupernova models improve the agreement with the observed abundance ratios.

Property of SN explosion

We perform two-dimensional hydrodynamical and nucleosynthesis calculations of jet-induced SNe and HNe of Pop III 40 $M_\odot$ stars and investigate the dependences of SN nucleosynthesis on the properties of the jet. We reveal the followings:

(1) SN nucleosynthesis is determined by the fallback onto the central remnant and the

strength of the shock heating. Since the property that influences the both effects is the energy deposition rate ($\dot{E}_{dep}$), $\dot{E}_{dep}$ is the most important property.

(2) The models with the smaller $\dot{E}_{dep}$ yield the smaller Fe production and the higher [C/O], [C/Mg], and [C/Fe]. The abundance patterns of the EMP stars, the C-enhanced EMP (CEMP) stars ([C/Fe]>1), and the hyper metal-poor (HMP) stars (-6<[Fe/H]<-5 and [C/Fe]~4) are reproduced by the models with $\dot{E}_{dep}=30\times10^{51}$ ergs s^{-1}, $3\text{-}2.3\times10^{51}$ ergs s^{-1}, and $1.5\text{-}0.5\times10^{51}$ ergs s^{-1}, respectively. The amounts of Fe ejection are $M(Fe)\sim0.1\ M_\odot$, $10^{-3}\text{-}10^{-4}\ M_\odot$, and $10^{-6}\ M_\odot$, respectively.

(3) The yields of jet-induced SNe depend on the properties of the jet. Thus, we can constrain the properties of the parent SN from the abundance patterns of the metal-poor stars. In particular, since [Sc/Fe] is larger for the explosion with the more collimated jet, it can be an indicator of the jet collimation, i.e., the asphericity of the explosion.

(4) The yields of the jet-induced SNe are similar to those of the one-dimensional model applied the mixing-fallback model. This confirms that the mixing-fallback model mimics the jet-induced explosion well.

III. Connection between GRBs and EMP stars

Long-duration GRBs are thought to be connected with luminous and energetic SNe (i.e., HNe) resulting from the black-hole forming collapse of massive stars. For recent nearby GRBs 060505 and 060614, however, the expected SNe have not been detected. The upper limits to the SN brightness are about 100 times fainter than GRB-associated HNe, corresponding to the upper limits to the ejected ^{56}Ni masses of $M(^{56}Ni)\sim10^{-3}\ M_\odot$.

The upper limit of $M(^{56}Ni)$ is consistent with the jet-induced explosion models for the CEMP and HMP stars. The jet-induced SN models can explain both GRB-HNe and GRBs without bright SNe in a unified manner with the different $\dot{E}_{dep}$. Therefore, we propose the connection between GRBs and the EMP stars: (1) the explosions with large $\dot{E}_{dep}$ are observed as GRB-HNe and their yields explain the abundances of normal EMP stars and (2) the explosions with small $\dot{E}_{dep}$ are observed as GRBs without bright SNe and are responsible for the formation of the CEMP and the HMP stars.