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研究課題名（英文）Simulation of multicolor light curves and spectra for the first supernovae in the Universe: from superluminous to faint supernovae

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研究成果の概要（和文）：本研究の主目的は、宇宙初期の初代星・低金属量星の起こす超新星爆発を将来観測で検出するために必要な、光度曲線とスペクトルのテンプレートを計算することである。初代星起源の超新星爆発の検出は、初代銀河の形成、宇宙初期の再電離及び化学元素汚染、さらに超巨大ブラックホールの起源を探る上で貴重な手がかりとなる。この目的を達成するために、様々な性質の低金属量星起源の重力崩壊型超新星爆発モデルについて多色光度曲線の計算を行った。計算の結果、高度曲線が平坦になるプラトーフェーズで見られる特徴的な色進化が、将来観測で初代星・低金属量星起源の超新星爆発を検出する決め手となりうることが分かった。

研究成果の概要（英文）：Recent theoretical studies show that Pop III and metal-poor supernovae (SNe) will be visible in the NIR and optical bands for z ~ 0.01 - 30 by many current and future surveys: WISH, WFIRST, JWST, PTF, Pan-STARRS, LSST. The main purpose of this research is to calculate light curve and spectra templates that are in demand for finding and fast identification of first SNe. The observation of Pop III SNe is a potential to directly probe the properties of the first stars, which are the key to the formation of primitive galaxies, early cosmological reionization and chemical enrichment, and the origin of supermassive black holes. In accordance with the purpose of research multicolor light curves for a number of metal-free core-collapse SN models have been calculated. It was found that color evolution of the plateau phase is helpful for identification of zero- and low- metallicity SNe by current and future transient surveys.

研究分野：天文学

キーワード：First supernovae　superluminous supernovae　photometry　identification　detectability

１．研究開始当初の背景

We have only ever seen 2nd generation (Pop II) stars and later. The first stars (Pop III) stars lie beyond the reach of current ground- and space-based telescopes. That is why there are not yet any observational constraints on their properties. In these circumstances the final result of the evolution of Pop III stars becomes important for observations. The early numerical simulations of Pop III stars suggest that they are very massive (100-500 $M_\odot$), but there is growing evidence, that some Pop III stars may be less massive (10-100 $M_\odot$). For masses 10-40 $M_\odot$ stars undergo Type II supernovae (core-collapse SNe (CCSNe)) or hypernovae. For more massive stars with masses 140-260 $M_\odot$ stars likely to explode as pair-instability supernovae (PISNe). Recent radiation hydro models of Pop III SN light curves showed that these explosions will be visible out up to z ~ 30 with JWST, WFIRST, WISH in near-infrared (NIR) and up to z ~ 2 by LSST in optical bands. There are several approaches in finding the supernova explosions of the first stars. One approach is to search for high-redshift superluminous supernovae (SLSN) (Tanaka et al. 2012; de Souza et al. 2013; Whalen et al. 2013). There is also a possibility of identification of supernova shock breakouts at high redshift (Tominaga et al. 2011). Another approach is to search supernova in metal-free pockets (see observations of gas clouds by Fumagalli et al. (2011)). Metal-free pockets extend the identification of the first star explosions up standard core collapse supernovae and even to faint supernovae. An intriguing question is then whether, if any, such supernova could be identified based on light curves from multi-band photometric observations. If so, how the light curve vary with other properties of the progenitor such as an initial mass, an evolutionary state (red or blue supergiant), and/or explosion energy? The exploration of the light curves and spectra with various properties indicated above would provide a powerful tool to interpret the data available from advanced instruments in future/current dedicated surveys. Last years I work with powerful radiation hydro codes (Tolstov 2010, Tolstov et al., 2015) which can be used to create this kind of tool.

２．研究の目的

Recent theoretical studies show that Pop III SNe will be visible in the NIR and optical bands for z ~ 0.01 - 30 by many current and future surveys: WISH, WFIRST, JWST, PTF, Pan-STARRS, LSST. The purpose of the research is to calculate light curve and spectra templates that are in demand for finding and fast identification of first SNe. The observation of Pop III SNe is a potential to directly probe the properties of the first stars, which are the key to the formation of primitive galaxies, early cosmological reionization and chemical enrichment, and the origin of supermassive black holes.

３．研究の方法

For light curves and spectra modeling I use the code STELLA modified with my own code RADA (fully Relativistic rADiative transfer Approximation).The time-dependent equations are solved implicitly for the angular moments of intensity averaged over fixed frequency bands. The number of frequency groups available for current workstation computing power typically 100-300 in the range from 10^{-2} to $5 \cdot 10^4$A is adequate to represent with reasonable accuracy the non-equilibrium continuum radiation. STELLA includes in full opacity photoionization, free-free absorption, lines (up to 26 millions) and electron scattering. Thus, the method of complete multigroup radiation hydro is used in which the defects of older approaches were corrected. The calculated light curves and spectra forms the templates which will be used for predictions, analysis and interpretation of the observational data.

４．研究成果

We have calculated the light curves for a number of hydrodynamical models for metal-free and low-metallicity 25-100 $M_\odot$ core-collapse supernovae and hypernovae. The radiation-hydrodynamical simulations reproduce in detail the shock breakout, plateau phase, and radioactive tail of the light curves. Blue supergiants are typical presupernova for Pop III core-collapse SNe with 40-60 $M_\odot$ and their structure determines the properties of shock breakout: shorter duration and lower luminosity compared to more massive red supergiant progenitors. The plateau phase is common to both blue supergiant and red supergiant models and can provide confirmation that the progenitors are similar to those of SN II-P. However, the duration of the plateau phase is often

unknown based on observations. The evolution of the photospere's velocity and multiband light curves can be more useful for the identification of Pop III SNe. We have found that the flat color evolution curve B - V during the plateau phase can be used as an indicator of low-metallicity SNe. The low amount of 56Ni used to explain carbon enhances metal-poor stars with mixing-fallback leads to a sharp luminosity decline after the plateau phase. This feature also can be used as an indicator of a low-metallicity progenitor. We have modeled Pop III SNe with one-dimensional simulations. The aspherical effects are taken into account approximately with the mixing-fallback model. The mixing of H and 56Ni could have a large impact on the shape of the light curve and future multi-dimensional radiation calculations are needed to investigate more accurately the effects of asphericity.
The direct detection of Pop III core-collapse SNe is hardly possible at high redshift (Whalen et al. 2013), but Pop III hypernovae will be visible to the James Webb Space Telescope at z ~ 10-15 (Smidt et al. 2014). The probability of the detection of Pop III SNe in metal-free gas pockets (z ~ 2) would be higher because their detection would be possible with current surveys (HSC/Subaru). Along with Pop III SNe, the results our modeling would be suitable for the identification of low-metallicity supernovae in the nearby universe.The number of discovered faint supernovae is increasing and new surveys such as LSST and JWST are planned to make a large contribution to the detection of low-metallicity supernovae.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計７件）

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④ Tolstov, Alexey; Nomoto, Ken'Ichi; Tominaga, Nozomu; Ishigaki, Miho; Blinnikov, Sergei; Suzuki, Tomoharu, Core-Collapse Supernovae in the Early Universe: Radiation Hydrodynamics Simulations of Multicolor Light Curves, The Lives and Death-Throes of Massive Stars, Proceedings of the International Astronomical Union, IAU Symposium, Volume 329,2017,pp. 451-451,10.1017/S174392131700254X, Not Refereed

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〔学会発表〕（計 9件）

① Alexey Tolstov
"Supernovae from 8-12 solar mass stars: multicolor light curve simulations"
660. Wilhelm und Else Heraeus-Seminar "Supernovae - From Simulations to Observations and Nucleosynthetic Fingerprints",
Jan 21-24, 2018
Physikzentrum Bad Honnef, Germany

② Alexey Tolstov
"The first supernovae in the early Universe: radiation hydrodynamics simulations"
Deciphering the violent universe
Dec 11-15, 2017
Playa del Carmen, Mexico

③ Alexey Tolstov
"Scenarios of superluminous supernovae in radiation hydrodynamics simulations"
"Workshop "Theories of Astrophysical Big Bangs".
6-11 November 2017
RIKEN, Wako, Japan

④ Alexey Tolstov
Ultraviolet emissions from superluminous supernovae: CSM vs. PISN vs. Magnetar
Stellar Evolution, Supernova and Nucleosynthesis Across Cosmic Time
18-29 September,2017
Kavli IPMU, Japan

⑤ Alexey Tolstov
Superluminous supernova models: from X-ray to near-infrared photometry
Workshop on the progenitor-supernova-remnant connection
July 24-28, 2017
Ringberg, Germany

⑥ Alexey Tolstov
"Core-Collapse Supernovae in the Early Universe: Radiation Hydrodynamics Simulations of Multicolor Light Curves"
10th IAU Symposia on Massive stars
30 Nov 2016
Spencer on Byron Hotel, Auckland, NZ

⑦ Alexey Tolstov
"Photometric identification of Population III core-collapse supernovae: multicolor light curve simulations"
First Stars V
1 Aug 2016
Stadthalle of Heidelberg, Heidelberg, Germany

⑧ Alexey Tolstov
"Population III core-collapse supernovae: numerical simulations of multicolor light curves"
2nd NAOJ-ECT Workshop on Many Riddles About Core-Collapse Supernovae: 1 Bethe and Beyond
30 Jun 2016
NAOJ, Mitaka, Tokyo

⑨ Alexey Tolstov
"Multicolor light curves simulations of Population III core-collapse supernovae: from shock breakout to 56Co decay"
14th International Symposium on Nuclei in the Cosmos XIV
21 Jun 2016
Toki Messe, Niigata, Japan

〔図書〕（計 0件）

〔産業財産権〕

○出願状況（計 0件）

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○取得状況（計 0件）

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権利者：
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〔その他〕

ホームページ等

① Kavlli IPMU News IPMU NEWS(IPMU Press Release)
http://www.ipmu.jp/en/20160711-BlueAndMetal

② IPMU Press Release: Ultraviolet light from superluminous supernova key to revealing explosion mechanism
https://www.ipmu.jp/en/20170907_Gaia16apd

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