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長瀧天体ビッグバン研究室

Astrophysical Big Bang Laboratory

PI: Shigehiro Nagataki (Ph.D of Science), Associate Chief Scientist

1. Abstract

Our group focuses on unveiling the mysteries surrounding astrophysical explosive phenomena such as supernovae and gamma-ray bursts from a theoretical point of view. Supernovae and gamma-ray bursts are believed to be the most energetic bombs in our Universe, and yet very little about their explosion mechanisms is known. Members of our group use frontier physics in their daily routine to attack these problems in high-energy astrophysics. In many cases, we seek power from the quickly advancing supercomputing resources in Japan to make progress in our investigations. These 'astrophysical big bangs' continue to fascinate us with their unknown physics and puzzling astronomical phenomena (e.g. gravitational waves, r-process nucleosynthesis, particle acceleration, high-energy neutrinos/gamma-rays, ultra high-energy cosmic rays, etc), and they are regarded as the most representative manifestations of the extreme Universe. Through our theoretical and computational endeavors, we strive to reveal the complete pictures of these violent explosions and provide state-of-the-art physical interpretations and predictions for future observations by the next-generation astronomical observatories. We are more than passionate to co-operate with fellow RIKEN researchers and all other interested groups in Japan and the World, and together we will realize a Utopia for researchers in RIKEN.

2. Major Research Subjects

(1) Explosion Mechanism of Supernovae and Gamma-Ray Bursts
(2) Origin of Rapid-Process Nuclei in the Universe
(3) High-Energy Particle Production in Supernovae and Gamma-Ray Bursts

3. Key Words

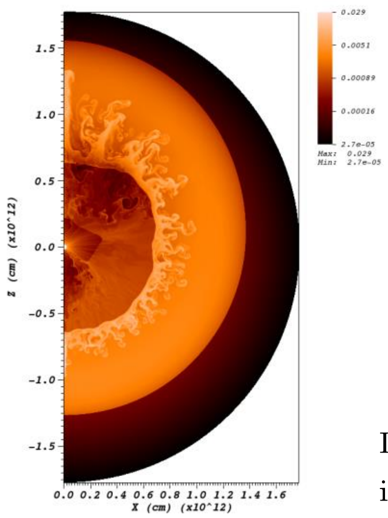
Supernova Explosions, Gamma-Ray Bursts, Explosive Nucleosynthesis, Equation of State for Dense Matter, High-Energy Cosmic Rays, High Performance Super-Computing

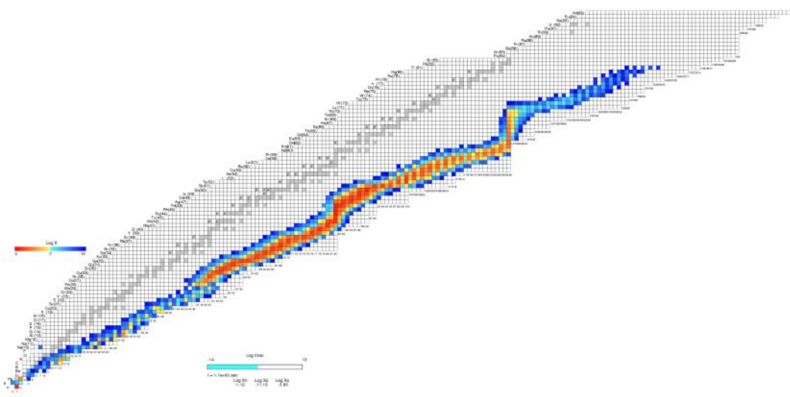
4. Summary of Research Activity

(1) Explosive nucleosynthesis in core-collapse SNe

Core-collapse supernovae (CCSNe), the death of massive stars, are one of the most drastic explosions in the Universe. However, the mechanism of CCSNe has not been understood theoretically even by recent supercomputing efforts. Multi-dimensional effects would be the keys to understand the mechanism. Therefore, 3-D simulations of CCSNe are highly desired although they are typically very challenging. For example, hydrodynamical instabilities affect not only the feasibility of the explosion but also the mixing of the ejected matter, which is partly composed of newly-synthesized heavy elements (e.g., radioactive 56Ni and even heavier metals) born in the explosive nucleosynthesis. Actually, observations of SN 1987A (the most frequently observed SN) imply that some 56Ni synthesized is conveyed into outer layers of the star by the mixing in contrast with simple spherical (i.e. 1-D) estimations. However, satisfying theoretical explanation of this mixing has not yet been deduced.

CCSNe play an important role as factories of heavy elements, e.g., "Gold". If rapid neutron capture process (r-process) occurs in CCSNe, heavy elements including Gold could be synthesized. However, the specific type(s) of CCSNe that can realize the r-process, or whether CCSNe are responsible for the creation of r-process elements in the first place are not clear. Recently, the Radioactive Isotope Beam Factory (RIBF) facility in RIKEN are starting to unveil the important features of unstable nuclei related to r-process. Our group tries to figure out the mechanism of CCSNe and the origin of heavy elements using state-of-the-art numerical simulations and the most up-to-date experimental results obtained by RIBF.





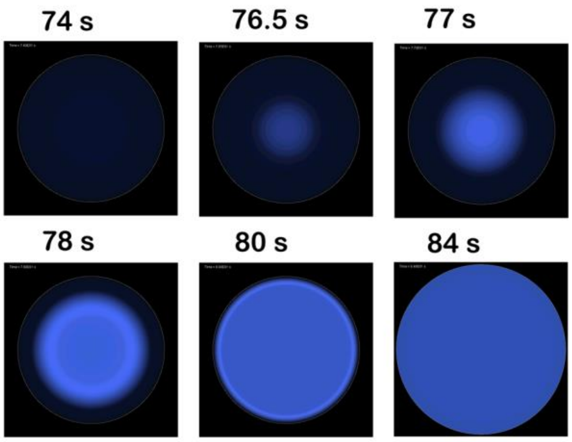
Left: An example of CC-SN simulation where fluid instabilities are growing. Upper: An Example of nuclear reactions in nuclear chart in CCSNe.

(2) Emission of supernovae and radiative transfer

The phenomenon of supernovae in most cases should start with a bright flash, caused by a shock wave emerging from the surface of the progenitor stars after the phase of collapse or thermonuclear explosion in their interiors. The detection of such outbursts associated with the supernova shock breakout can be used to obtain information about the explosion properties and pre-supernova parameters, which is necessary to understand the physical processes that underlie this phenomenon.

Study of supernova shock breakouts has become particularly timely owing to the recent detections of this phenomenon by the SWIFT and GALEX missions. The number of future/ongoing wide and/or deep-field surveys capable of observing shock breakouts is also increasing dramatically, including PTF, LOSS, CRTS, KWFC, Skymapper, DES, Pan-STARRS and Subaru/HSC, LSST.

Shock propagation at the epoch of shock breakout cannot be considered as adiabatic, which makes it difficult to construct analytical solutions. This necessitates the usage of numerical calculations of the process in which radiative transport plays a very important role. Our group approaches this problem using multi-group radiation hydrodynamics codes STELLA and RADA that allow us to calculate shock breakout for compact pre-supernovae and take into account a number of relativistic effects.

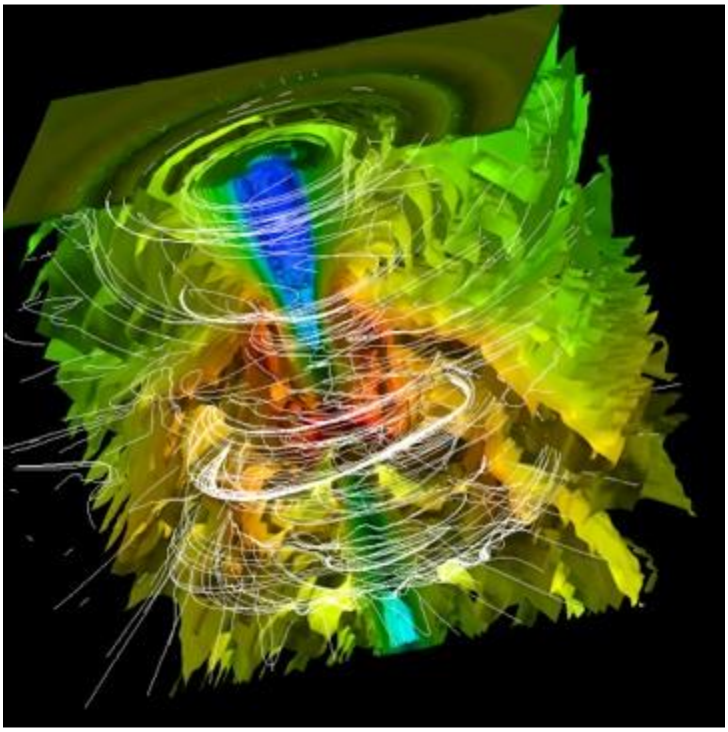


The calculated dynamics of the outburst of a star (shock breakout and supernova), as if it would be visible to an observer.

(3) 3-D general-relativistic magnetohydrodynamics

It is an observational fact that some gamma-ray bursts (GRBs) happen together with CC-SNe. The explosion energy of these supernovae can be ten times larger than that of normal core-collapse supernovae. Therefore, the central engine of GRBs should be entirely different from normal core-collapse supernovae, although its detailed mechanism is still poorly understood. We are challenging ourselves to understand the explosion mechanism with help of super-computing power, by developing the state-of-the-art General Relativistic Magneto-Hydro Dynamic (GRMHD) code, a.k.a. the YAMATO code (YAMATO "大和" is the historic name of "JAPAN").

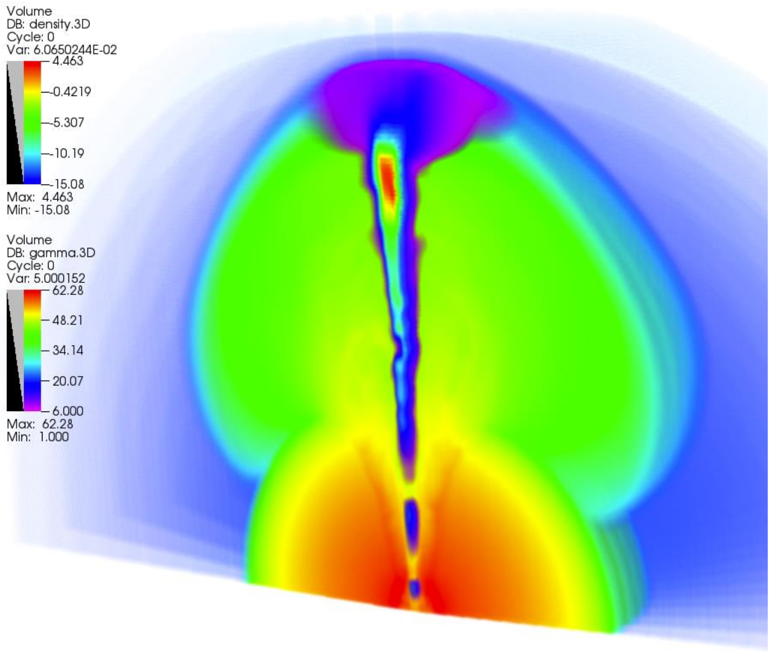
We are particularly interested in the mechanism of energy extraction from a rotating black hole which is expected to form as a result of the core-collapse of a rapidly rotating massive star. In principle, according to general relativity, it is possible to extract rotational energy from a rotating black hole. We are investigating whether this effect is self-sufficient to drive the most powerful explosions in the Universe (GRBs+CC-SNe) .



An example of 3-D GRMHD simulation on formation of a relativistic jet using YAMATO code.
The rapidly rotating black hole is driving a relativistic jet with a help of magnetic fields (white lines). Colors represent density contours.

(4) GRB jet propagation in progenitor stars

A grand challenge in the GRB jet is to construct a self-consistent theory that is responsible for the generation, acceleration, and collimation of the relativistic jet. The interaction of the relativistic jet with the progenitor star and interstellar medium is very important to reveal global dynamics and structure of the GRB jet. The hydrodynamic structure of the relativistic jet is also important in order to produce GRB emission. Our group investigates the physics of the propagation of the relativistic jet in the progenitor star through 3-D numerical simulations. The basic property of the propagation of the relativistic jet through the ambient medium is useful for understanding the jet dynamics in other systems such as AGNs and microquasars.

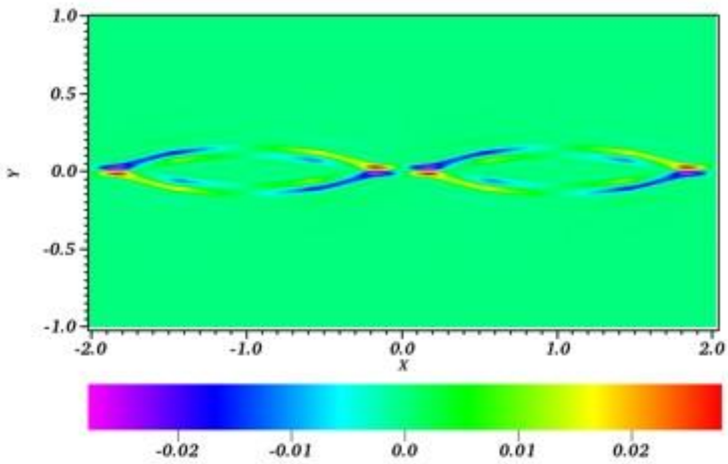


An example of numerical simulations on propagation of a relativistic jet in a progenitor star. The relativistic jet is believed to be a GRB later.

(5) Multi-fluid simulations of relativistic outflows

It is now well recognized that magnetic fields play a very important role in many astrophysical phenomena and in particular in those involving relativistic outflows. The magnetic fields are likely to be involved in launching, powering and collimation of such outflows. The dynamics of relativistic magnetized plasma can be studied using diverse mathematical frameworks. The most developed one so far is the single fluid ideal relativistic Magnetohydrodynamics (RMHD). The framework of resistive RMHD allows to incorporate this magnetic dissipation but the inevitably phenomenological nature of its Ohm's law puts constraints on its robustness. At the other extreme is the particle dynamics, describing the motion of individual charges in their collective electromagnetic field. The numerical stability considerations require particle-in-cell (PIC) codes to resolve the scales of plasma oscillations. The accuracy considerations can be even more demanding, pushing towards the particle gyration scales.

Somewhere in between lies the multi-fluid approximation, where plasma is modeled as a collection of several inter-penetrating charged and neutral fluids, coupled via macroscopic electromagnetic field and inter-fluid friction. Undoubtedly, this approach is not as comprehensive in capturing the microphysics of collisionless plasma as the particle dynamics (and kinetics) simulations. However, it does this better than the single-fluid MHD treatment. The ability of two-fluid approach to describe accurately the magnetic reconnection phenomenon is probably the most important advocate for this method. The inter-fluid friction term is analogous to resistivity. In the absence of exact analytic solutions of equations with non-vanishing inter-fluid friction term, we are forced to try problems for which this term is expected to be of critical significance. This important problem merits a comprehensive study, which we are planning to carry out in the near future.

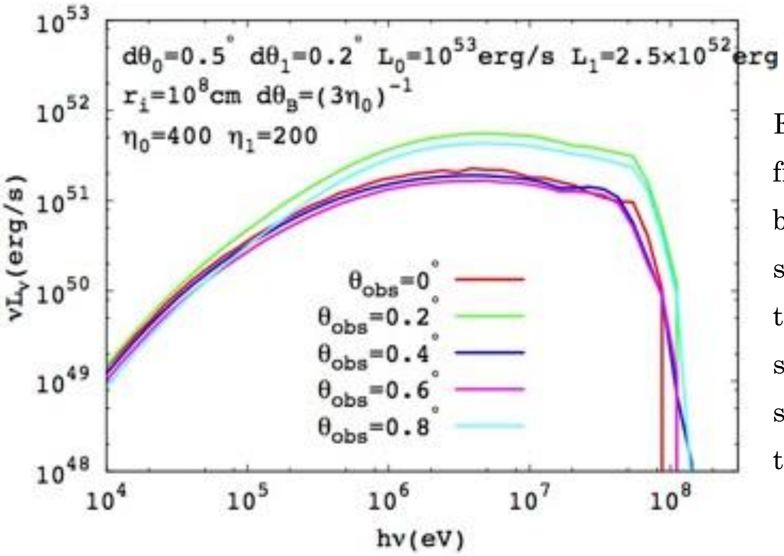


An Example of two-fluid ideal relativistic Magnetohydrodynamics (RMHD) simulations developed by Barkov and his collaborators in 2014.

(6) Emission Mechanisms of Gamma-ray Bursts

Gamma-ray burst is the most luminous phenomena in the Universe. It is believed to be induced by an ultra-relativistic jets originating from a compact objects. However, exactly how the gamma-rays are produced within the jet is still under hot debates. Recently, the so-called “photospheric emission model” is considered to be one of the most promising candidates for GRB emission mechanism. In this model, the gamma-rays are emitted from the jet when it becomes transparent to radiation. Since the interaction with the jet material plays an important role in determining the properties of the emitted gamma-rays, detailed radiative transfer calculations are essential to model the GRB photospheric emission.

In our group, we approach this problem by performing Monte Carlo simulations that solve the propagation of gamma-rays within the jet. We are particularly interested in how the hydrodynamical structure of the GRB jet influences the properties of the resultant emission, including its spectrum, polarization and light-curve. Starting from a series of toy models of jet structures, we are investigating the conditions under which the photospheric emission can successfully reproduce the observed characteristics of GRBs.

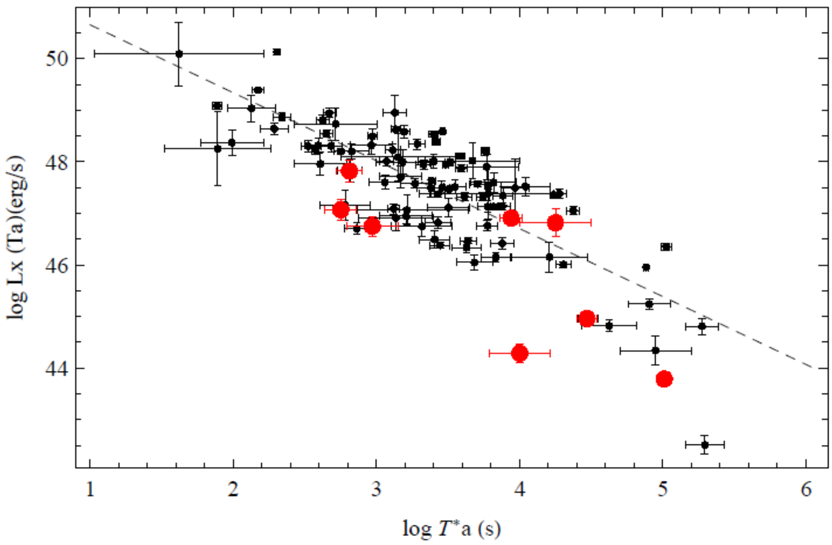


Example of emission spectrum from a relativistic jet obtained by performing a Monte Carlo simulation of radiative transfer. Jets having a stratified structure can successfully reproduce the typical spectrum of GRBs.

(7) Gamma-ray Bursts as Cosmological Tool

GRBs are the farthest and the most powerful objects ever observed in the universe and therefore can be useful probes for testing cosmological models. To this end, it is crucial to understand if they can be considered as standard candles (astronomical objects whose luminosity is known or can be derived from other distance-independent observables). At first sight, GRBs seem to be far from standard candles, with their energies spanning over 8 orders of magnitude. However, discovering universal relations among the observables properties of GRBs plays a crucial role in determining whether they can be considered standard candles and can provide insight into the processes responsible for GRBs.

Within this framework, Dainotti et al. (2008) discovered a (see figure). This correlation has been updated (Dainotti et al. 2010) used as possible redshift estimator (Dainotti et al. 2011a), applied as cosmological tool (Cardone et al. 2009;2010) recently corrected for selection effects (Dainotti et al. 2013a). Caveats on the use correlations not corrected by selection effects has been presented (Dainotti et al.2013b) showing how we can commit errors on the evaluation of the cosmological parameters. Nowadays, the challenge is the use of the intrinsic correlation to explain the most plausible theoretical models and to apply as a cosmological tool.

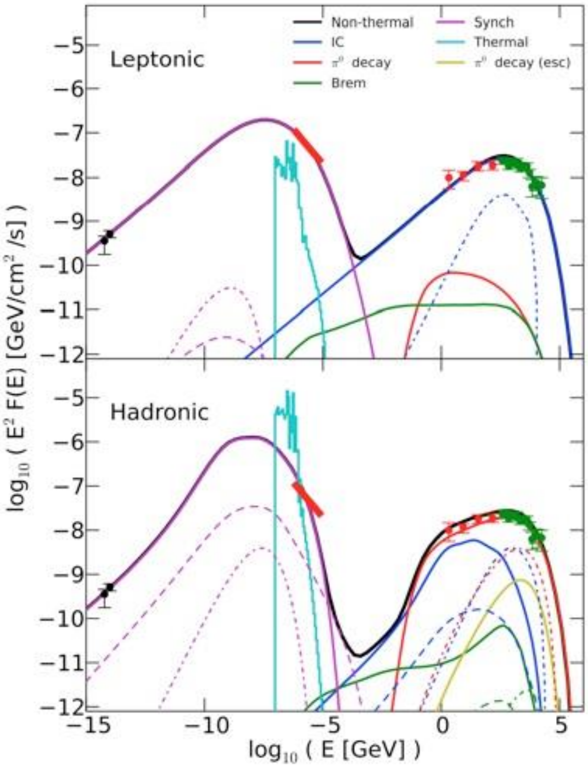


The new correlation for long GRBs between the X-ray luminosity at the end of the plateau phase, LX and its duration, T*a, found by Dainotti et al. 2008, 2010.

(8) Supernova Remnants

Our research activities also involve the study of cosmic rays (CRs) with a Galactic origin, especially on their very probable link with supernova remnants (SNRs), using the latest numerical techniques and sometimes also analysis of observation data from space telescopes. SNRs are objects known to emit very energetic photons in X-ray and Gamma-ray, that must be produced by local populations of high-energy particles. Existence of strong collision-less (magnetic) shocks have been confirmed in SNRs, which can indeed accelerate charged particles locally to relativistic energies via the Nonlinear Diffusive Shock Acceleration (NL-DSA) mechanism with very appreciable efficiencies. Unfortunately, the confirmation of CR production at SNRs and their shocks is a very nontrivial task since CRs are deflected by the magnetic field in the Milky Way and hence cannot be measured directly from their sources. However, many SNRs can be observed across the whole frequency spectrum, spanning from radio to TeV gamma-ray energies. A good understanding of the multi-wavelength emission from these cosmic accelerators is absolutely key to unravel the long-standing puzzle of Galactic CR origin.

Our group performs 1-D (with micro-physics) and global multi-D hydrodynamical simulations to study the dynamics, particle acceleration, broadband emission and neutrino production for various types of SNRs. Our results can be directly compared with current and future observations from radio to TeV energies to accurately quantify the contribution of SNRs to the production of CRs within Milky Way and in other galaxies similar to ours. Meanwhile, we have started to tie our codes to dedicated multi-D simulations of SN explosions and nucleosynthesis, that will provide us a consistent evolutionary picture of the very last stages of stellar evolution and their contributions to chemical enrichment of the interstellar space.



Modeling the multi-wavelength spectrum of the famous young SNR Vela Jr from radio to TeV gamma-ray using our CR-Hydro-NEI code.

The top and bottom panels show two representative models where the gamma-rays are predominantly produced by leptonic (CR e-) and hadronic (CR ions) particles respectively.

(9) Other topics

We are also interested in the origin(s) of ultra high-energy cosmic rays (UHECR) and high-energy neutrinos, cosmic particles that are often thought to come from extra-galactic space at extreme distances. Along with construction of theoretical models, we also try to find clues from data gathered by the latest astro-particle experiments. Several individuals of our team are team members of the Telescope Array experiment, a ground-based air-shower detector in Utah that studies very high-energy CRs hitting our atmosphere from outer space.

Currently, a few of us are also involved in activities of the Cherenkov Telescope Array

(CTA), a near-future international ground-based observatory for very high energy (VHE) gamma-rays. We are performing theoretical and numerical calculations to help the team make plans for future observations of various high-energy astrophysical objects using CTA.

Principal Investigator

長瀧　重博　　Shigehiro Nagataki

Core Members

Shiu-Hang Lee

Maxim Barkov

伊藤　裕貴　　Hirotaka Ito

松本　仁　　Jin Matsumoto

Maria Giovanna Dainotti

Alexey Tolstov

Jirong Mao

Past Core Members

小野　勝臣　　Masaomi Ono

Long Term Visitors

Donald Warren (from NCSU)

Andrea Boria (from Jagellonian Univ.)

Short Term Visitors

内山　泰伸　　Yasunobu Uchiyama

滝脇　知也　　Tomoya Takiwaki

長峯　健太郎　Kentaro Nagamine

Assistants

蟹　裕子　　Hiroko Kani

倉持　千加子　Chikako Kuramochi

佐々木　一枝　Kazue Sasaki

木寺　明子　　Akiko Kidera