Simulation of Supernova Explosion Accelerated on GPU: Spherically Symmetric Neutrino-Radiation Hydrodynamic

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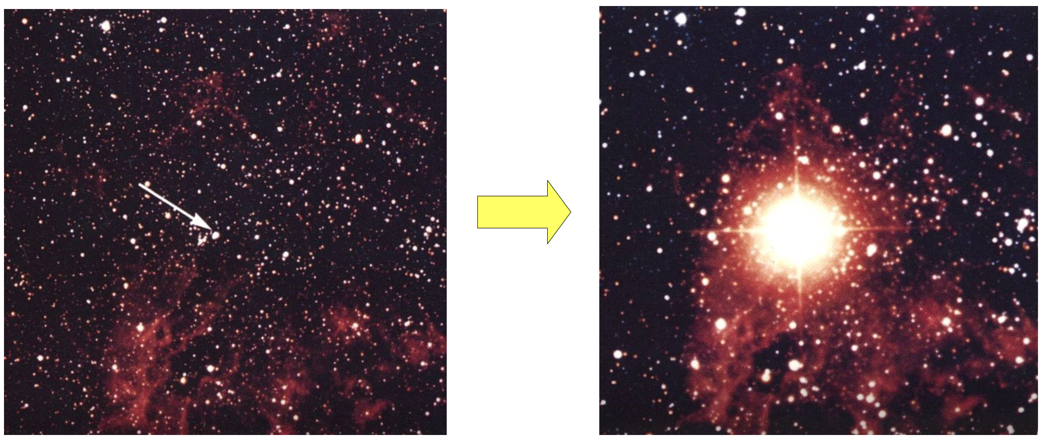
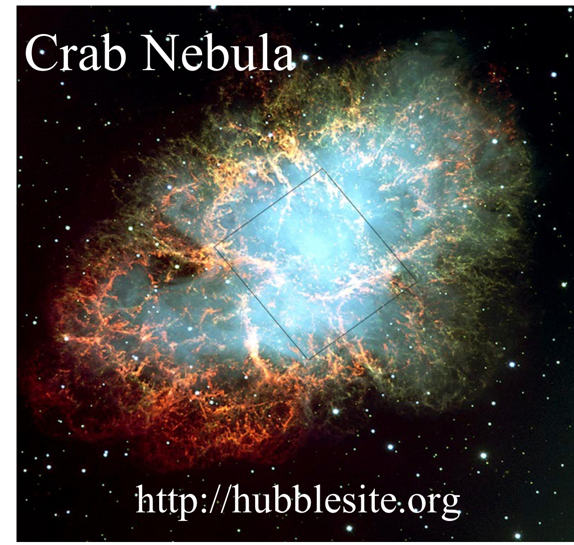
Introduction

Supernova explosion

- Example: 1987A (in large Magellanic Cloud)



A.K.Mann "Shadow of a Star" (W.H. Freeman and Company, 1997)



Core collapse supernovae

- Half the number of supernovae
- Stars with mass more than 10 times solar mass
- At the end of stellar life, nuclear fusion forms iron core and exhosts light elements

  → gravitational collapse → core bounce → explosion

Introduction

Detailed mechanism of core collapse supernova must be understood

- Formation of neutron starts and blackholes
- *Generation of heavy elemenets*
- Comparison with observational data (gamma rays, gravitational waves, energy emission, etc.)

- All the four fundamental forces play essential roles
  - Gravitational force (general relativity)
  - Properties of dense matter (strong/electromagnetic interactions)
  - Neutrino radiation (weak interaction) plays a crucial role

    – described by coupled equation of radiation transfer and hydrodynamics
- Can be understood only through large scale numerical simulations

Introduction

Large scale numerical simulation is essential to understand explosion mechanism

- Hydrodynamics
- *Boltzmann equation for neutrino transport (6-dimensional)*
- General relativity
- Equation of state of dense matter, neutrino reactions

- Fully 6D simulations are currently restrictive
  - Dimensionality plays an essential role for explosion
  - Approximations are often used for 2D/3D systematics
- Spherically symmetric system (1D): target of this work
  - Important for comparison with observational data
  - Systematic survey of massive stars is necessary
  - Basis of 2D/3D simulations
  - 1^{st} principle calculation (Full GR + Hydro + Boltzmann)

Introduction

High performance computing

- Two trends of architecture
- Massively parallel supercomputers
  - K-computer, Intel Xeon Phi, etc.
- Arithmetic accelerators
  - GPUs, Pezy-SC
  - Heterogeneous architecture: CPUs + devices
  - Currently not widely used in SN simulations in spite of large potential

This work: for establishing techniques to exploit heterogeneous architectures for supernova simulations

- Application to spherically symmetric system as a testbed

Implementation

- Numerical setup
  - GR Lagrangian hydrodynamics + S_N + Implicit scheme

    S. Yamada, ApJ 475 (1997) 720, A&A 344 (1999) 533
  - At every step of time evolution, solve a linear equation system
  - Iterative solver algorithm for a block tridiagonal matrix

$$M = \begin{pmatrix} B_1 & C_1 & 0 & & \dots & \\ A_2 & B_2 & C_2 & 0 & & \\ 0 & A_3 & B_3 & C_3 & & \\ \vdots & & \ddots & \ddots & \ddots & 0 \\ & & 0 & A_{n-1} & B_{n-1} & C_{n-1} \\ 0 & \dots & & 0 & A_n & B_n \end{pmatrix}$$

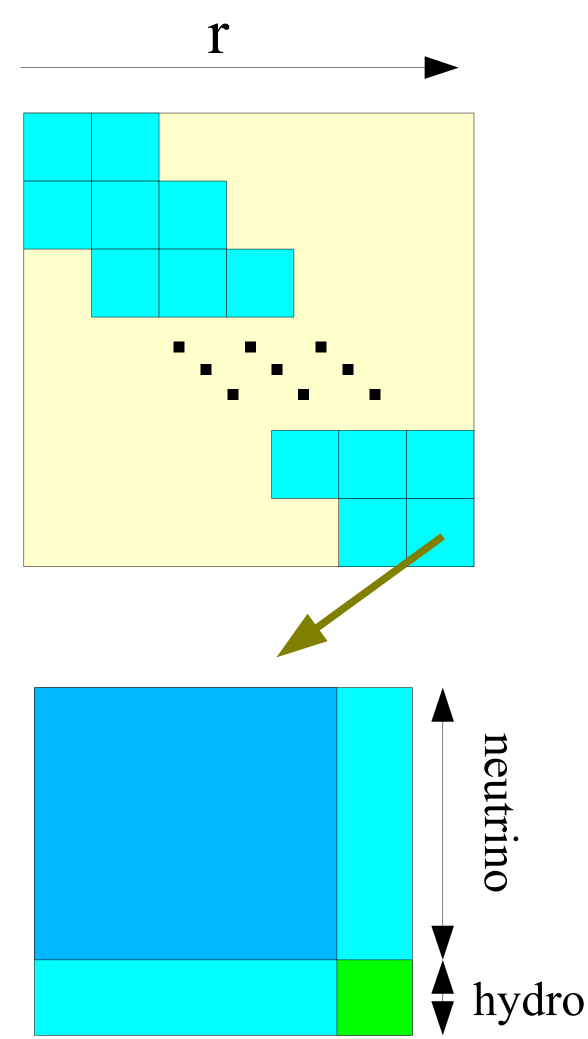
  - Rank of each block matrix: $N_{max} = N_{E_\nu} \cdot N_{\rm ang} \cdot N_\nu + N_{\rm hyd}$
  - Weighted Jacobi preconditioner

    A. Imakura et al. JSIAM Letter 4 (2012) 41
  - This linear equation solver is the first target of offloading

Problem setup

- Linear equation
  - At each spatial (radial) point r,
    - Neutrino dof.: energy, angle, species
    - Hydrodynamical dof.: velocty etc. (N_{hyd}=11)
    - Block tridiagonal matrix, each block is dense

    → matrix rank: $N_{max} = N_E * N_{ang} * N_\nu + N_{hyd}$
  - N_r = 256 → increased to 512, 1024 (preferable)
  - Required memory size = $N_{max}^2 * 4 * N_r * 8$ Byte



	set-1	set-2	**set-3**	set-4
N_r	256	256	256	256
N_E	14	16	**24**	32
N_{ang}	6	8	**12**	16
N_ν	4	4	**4**	4
N_{max}	347	523	1163	2059
memory	1 GB	2 GB	**9.3 GB**	32 GB

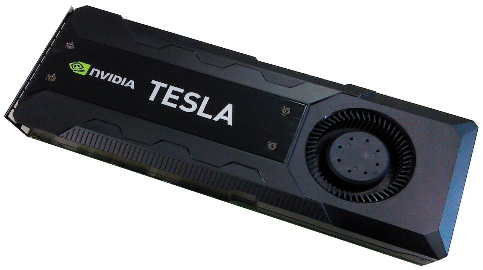
Practical choice of N_{max}

Implementation

- Offloading scheme
  - Base code: Fortran, MPI parallelized
  - C-code as intermediate code (for later convenience)
  - Device code is implemented with OpenACC
    - Directive-based framework for offloading
    - Portable, compatible with OpenMP 4.0
  - Multi-GPU: each MPI process handles one GPU device
  - Communication via host processes
- Two implementations
  - "Native" code
    - Tuned using OpenACC directives
    - Simple assignement of tasks to threads
  - cuBLAS code
    - Well-tuned BLAS library provided by NVIDIA
    - CUDA stream for asynchronous execution (in units of block matrix)

Machines

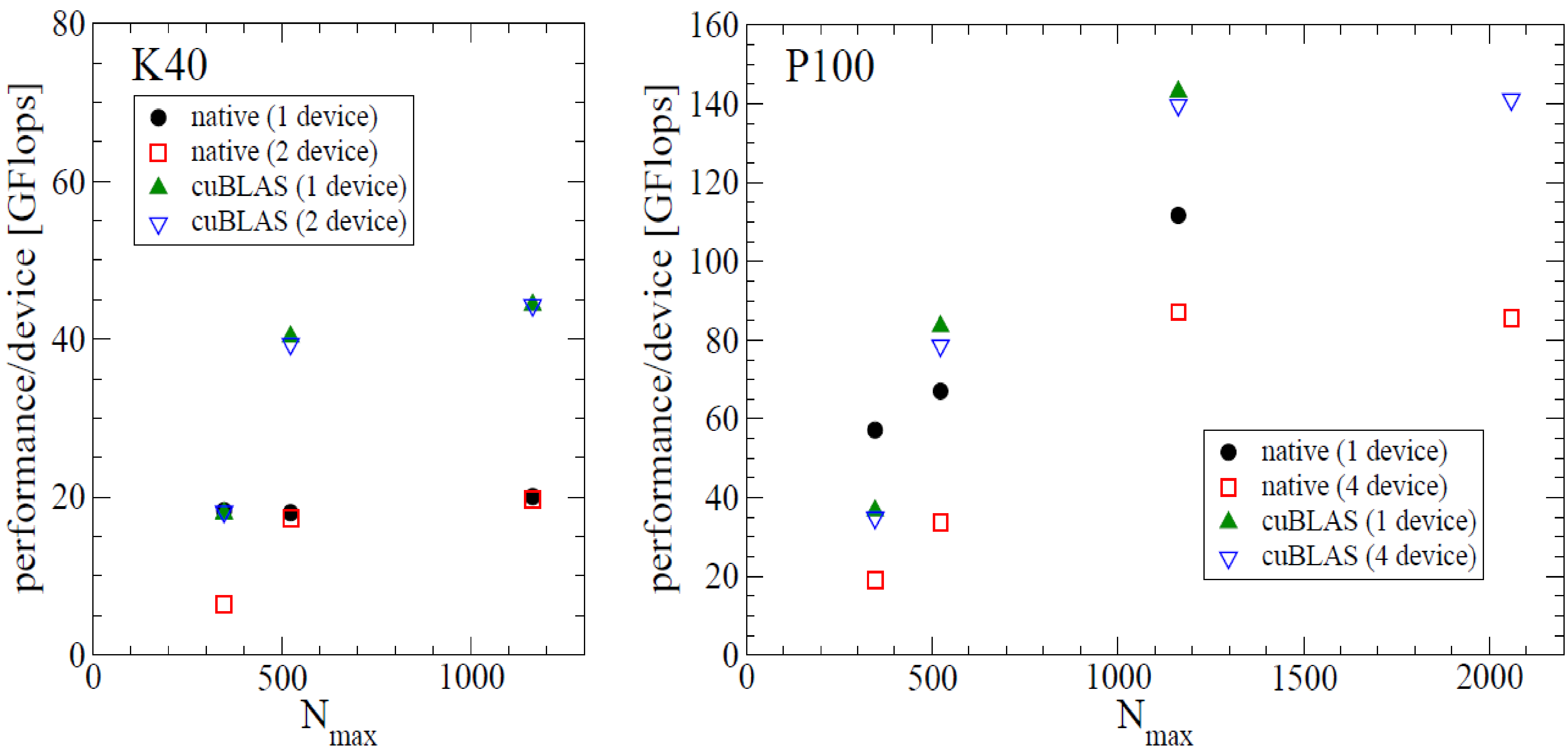
- Performance is measured on two machines at KEK
  - All arithmetic operations are in double precision
  - Compiler: PGI + OpenMPI + CUDA environment



	Xeon + Kepler	Power8 + Pascal
Host processor	Intel Xeon Haswell (6 core) x2	IBM Power8 (10 core) x2
Peak/core (double)	44.8 GFlops/core	22.9 GFlops/core
GPU	NVIDIA K40 x2	NVIDIA P100 x4
#core/device (double)	960	1792
Peak/device (double)	**1430 GFlops**	**4700 GFlops**
Memory size/device	**12**	**16**
Memory B/W	**288 GB/s**	**720 GB/s**
bus	PCIe Gen2 x16	NVLink (40GB/s x2)

Performance result

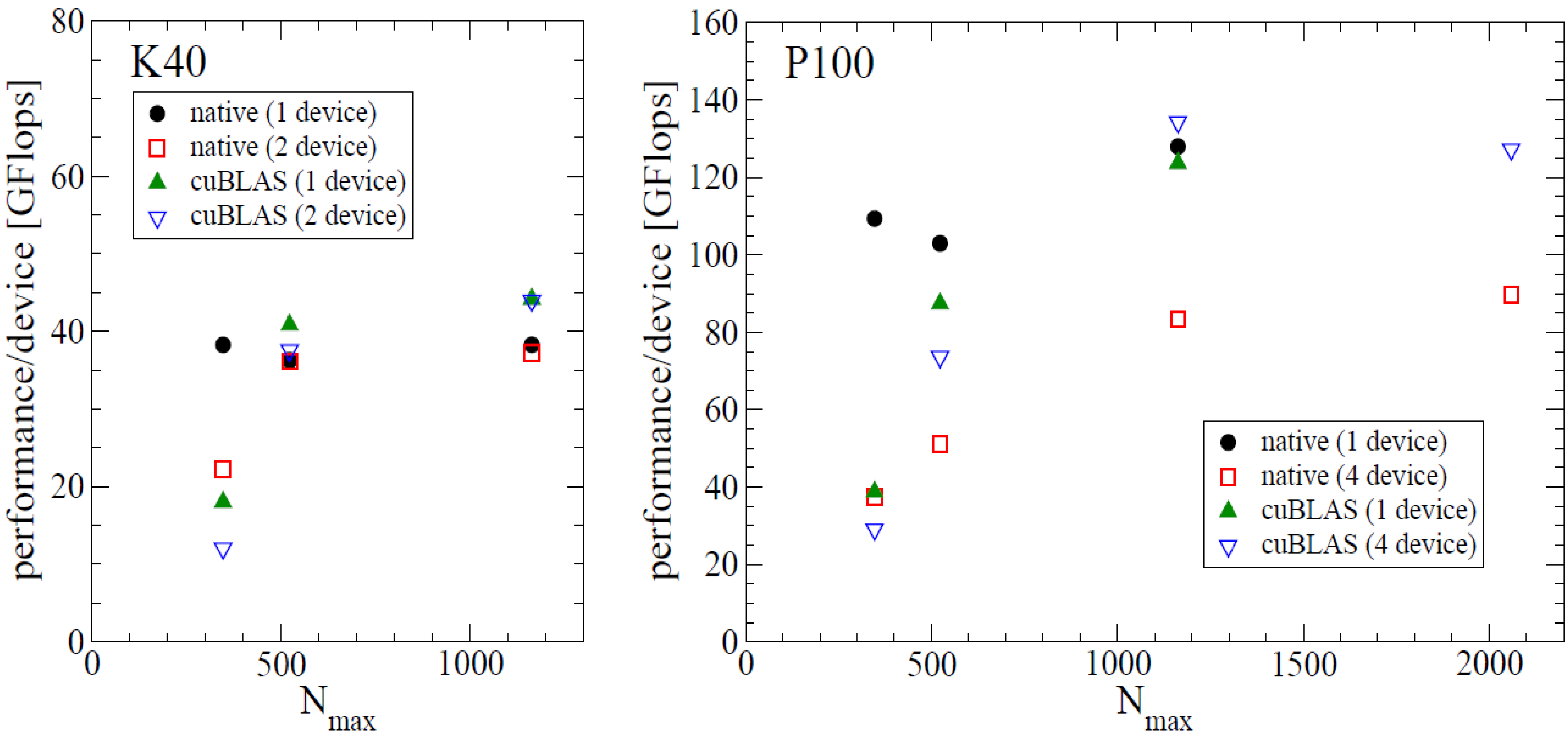
- M_D^{-1} : inverse of diagonal blocks (no communication)



  - cuBLAS code tends to be faster at large N_{max} region (~x1.5)
  - On Pascal, ~140 Gflops/device (3% of peak)

Performance result

- $M - M_D$: subdiagonal blocks (with communication)



  – Communication overhead is small ($\sim 1/N_{max} * [N_r/N_{dev}]$)

Acceleration of simulation

- How much is simulation accelerated ?
- Time consuming parts in evolution step
  - Dominant: matrix inversion
  - Subdominant: neutrino reaction (1/20 of matrix inv.)
  - Other parts are (currently) negligible

Result: next page ↓

- GPUs largely accelerate the linear solver
- Now dominant operations are:
  - Preparation of matrix (determination of weight parameter)
  - Neutrino reaction (computation collision term: integration)

→ Next targets of offloading

Acceleration of simulation

- Speed up
  - Elapsed time [sec] for original and offloaded codes
  - Xeon + Kepler: Nrmax=256, Nang=6, Ne=14

Xeon/Kepler (Set-1)	Np = 8	Np = 1	GPU (cuBLAS)
collision	4.9	40.5	
Matrix total	115.5	911.4	46.2
setup	5.1	40.2	40.8
Inversion (11 iter)	110.4	871.2	**5.4**

  - Power8 + Pascal (x4): Nrmax=256, Nang=8, Ne=16

Power/Pascal (Set-2)	Np = 16	Np = 4	GPU (cuBLAS)
collision	8.6	35.1	
Matrix total	168.0	622.5	45.9
setup	11.8	43.7	45.0
Inversion (7 iter)	156.2	578.8	**0.9**

Conclusion/outlook

- Conclusion
  - Acceleration of 1D neutrino-radiation hydrodynamics code by GPUs
  - Efficient development by using OpenACC (+cuBLAS)
    - cuBLAS becomes more efficient for larger block matrices, while OpenACC also works well
  - Large speed up for matrix inversion required in implicit scheme
    - GPU performance is not well exploited, but already enough fast
    - Other parts are to be accelerated urgently
    - Simulations with N_r=1024, N_{ang}=12, N_E=24 becomes practical

  → Application to systematic 1D simulations
- Outlook
  - Application to 2D, 3D code
  - Further optimization and improvement of algorithms
  - Pezy-SC: translation to OpenCL code is needed