Computer Center at NAOJ: Supercomputing Facilities and Products

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Abstract

The supercomputing facilities in the National Astronomical Observatory of Japan are open for astrophysicists in Japan. Based on a peer review system, about sixty proposals were approved, and numerical studies in various fields, from cosmology to formation of the moon, are intensively proceeding. I briefly review the computer system and their recent scientific products.

1 Super-computer Center in NAOJ

The national astronomical observatory (`http://www.nao.ac.jp/`) is located in a suburb of Tokyo, Mitaka, has many telescopes from the optical/infrared (Subaru telescope at Hawaii: `http://subarutelescope.org/`), radio (Nobeyama: `http://www.nro.nao.ac.jp`, VERA: `http://veraserver.mtk.nao.ac.jp/`) to the gravitational waves (TAMA: `http://tamago.mtk.nao.ac.jp/tama.html`). Besides these telescopes, we have a "telescope for theorists", namely a very powerful super-computer system in the Astronomical Data Analysis Center (`http://www.cc.nao.ac.jp/index-e.html`). There are many supercomputer centers in Japanese universities, but our system is quite unique on the following points.

Firstly, this is only for astrophysics, astronomy and related science. Probably our center is one of the most powerful systems for astronomy in the world. We have two sub-systems. One is a vector-parallel supercomputer, Fujitsu VPP5000 (Fig. 1), which has 60 processors with 960 GB memory and 12 TB hard disks. The other is the MUV, means Mitaka Underground Vineyard (Fig. 1). As represented by this nickname, 16 GRAPE-5s (Kawai et al. 2000) and 8 GRAPE-6s clusters (`http://grape.astron.s.u-tokyo.ac.jp/grape/`) are working at the basement of one of our buildings. The computer center is connected to major universities with 10-Gbit Super SINET (`http://www.sinet.ad.jp/english/super_sinet.html`). The total CPU power is 4.6 Tflops, We are also trying to combine the VPP5000 and GRAPE-cluster to solve evolution of hybrid-systems of the collisional N-body (like open clusters) embedded in a gas component. We also have a 60 TB tape library (SONY Petasite) and visualization system (SGI machines). Recently we have introduced a Virtual Reality system (the 4-D Digital Universe), with which we can analyze numerical results using the three-dimensional view of computational results (Fig.1).

Secondly, similar to standard observatories, we adopt a peer review system to assign CPU times to each proposal. We call for proposals biannually, usually in March and September. Several hundreds CPU hours for each VPP5000 project group are assigned, and there is no CPU limit for GRAPE users. Last year, about 60 projects were approved. The most important feature is, it is FREE to use our system! If you use the supercomputer center in universities to get the same CPU time and disk space, you would be required to pay several tens thousand dollars per year!

We replaced the whole system every 4 to 6 years so far. The current system was replaced in January, 2001. The total cost was about 20 million dollars.

2 Scientific Products

The 60 proposals for the VPP5000 and GRAPE system are working on various problems in quite a wide field of astrophysics; For examples, cosmology, cluster of galaxies galaxy formation and galaxies, dynamical and chemical evolution of galaxies, the Active Galactic Nuclei, interstellar medium, star-formation at low-z and high-z, neutron stars, jets from AGN and proto-stars/disk, accretion disks, solar flares, formation of planets, rings, and formation of Moon.

2.1 Cosmology and Cluster of galaxies

Many people are working on cosmology and cluster of galaxies. Yasushi Suto (Tokyo University) and his collaborators, one of heavy users in our system, is working on structure of the universe (e.g. Yoshikawa, et al. 2001; Hikage et al. 2001; Suginohara et al. 2002). See also Dr. Jin's paper in this proceedings book. A couple of groups (Funato; Yahagi) were also working on evolution of cluster of galaxies using N-body and hydrodynamical simulations.

2.2 MHD simulations

The majority of the proposals are categorized to the Magneto-Hydrodynamics. Some of them are in one-dimension (general relativistic shock propagation towards BH by Aoki), two-dimension (reconnection

Figure 1: Supercomputer Fujitsu VPP5000 (upper right panel), GRAPE system in MUV (left panel), and the 4-D Digital Universe (lower right panel)

model for solar flares/jets by Yokoyama et al.; accretion disks around neutron stars by Kato; reconnection in galactic disks by Tanuma et al.; jets from proto-star by Hayashi et al.), and three-dimensional simulations (accretion disks by Matsumoto et al.; jets from accretion disks by Kudo; shocked layers by Kuwabara et al. and Nakamura et al.; solar flares by Umekawa et al.; magnetic twisted tubes by Uchida et al. and Miyagoshi et al.). See also the paper by Ryoji Matsumoto in this volume

As an example, let me introduce an interesting work by Syuniti Tanuma (Nagoya University) on magnetic reconnection triggered by the Parker Instability in the Galaxy. Tanuma and his collaborators have found that the Parker instability creates the current sheet spontaneously, and triggers the magnetic reconnection in the Galactic halo. The magnetic reconnection creates hot gases ($> 10^5$ K) and high velocity(> 100 km s^{-1}) ‘bipolar ’ jets in the Galactic halo. Chimney-like structures are also formed. This work is quite interesting on a point that supernova explosions are not necessary to form hot chimney in galactic disks (cf. Norman & Ikeuchi 1989).

2.3 Galaxies and AGNs

In this field, many MHD simulations were performed on the accretion disks and jets by Matsumoto, Hayashi, Kudo, and their collaborators. I am working on structure of the obscuring materials around the AGN (Wada & Norman 2002). I also made numerical modeling of nearby galaxies, such as the Large Magellanic Cloud (Wada et al. 2000), and NGC 4303 (Colina & Wada 2000).

Here let me introduce briefly our starburst-driven torus model from Wada & Norman (2002). In the so-called unified model, the AGNs commonly harbor a geometrically thick dust ‘torus’ around the central engine. However, there are number of unsolved problems in the unified model. What is the mechanism to form and maintain the thick tori? What is the structure of the tori? Are they identical between type-1 and type-2 AGNs? Recent X-ray observations suggest contribution of the nuclear starbursts in some fraction of Seyfert 2 galaxies. We have performed 3-D hydrodynamical simulations of a self-gravitating disk around a super-massive black hole. We have found that if we assume energy feedback from supernova explosions in a 100 pc region around the black hole, an inhomogeneous, turbulent thick-disk, which look like a ‘concave lens’ rather than ‘doughnut’, is naturally formed. To achieve the high column densities ($> 10^{23}$ cm^{-2}) as suggested by recent X-ray observations of some Seyfert 2 galaxies with nuclear starbursts, the viewing angle should be larger than about 60° from the pole-on for a $10^8 M_\odot$ massive black hole. Due to the inhomogeneous internal structure of the torus, however, the observed column density is not a monotonic function of the viewing angles, and it fluctuates by a factor of order ~ 100. The average accretion rate toward $R < 1$ pc is $\sim 0.5 M_\odot$ yr^{-1}, which is twice larger than that in the model without the energy feedback.

2.4 Galaxy formation and primordial stars

Formation and evolution of galaxies are studied by Noguchi et al., Nakasato et al., Kobayashi et al., Koda et al., Ideta, Yoshioka, Habe, and Fukushige. See also Jun Makino's review in this volume. Toru Tsuribe has worked on the formation of the first stars under the CDM model, taking into account molecular hydrogen cooling. He used one million SPH particles to simulate star formation on a galactic scale, and found that dense knots, where the temperature is 200 K, and the mass is 1000 solar mass, are formed at the intersection of large-scale filamentary structures.

I have worked on the initial starbursts in proto-galaxies, in collaboration with A. Venkatesan (University of Colorado). Here I briefly summarize the results. We investigate dynamical and chemical effects of multiple supernova (SN) explosion in inhomogeneous primordial galaxies using three-dimensional hydrodynamical simulations. We found that 1) SN explosions dominate the dynamics of the gas in primeval galaxies of $10^7 M_\odot$, that 2) the gas component is almost completely blew-away by instantaneous 1000 SN explosions, and such bursts contribute to pollute the inter galactic gas (Fig. 2), and that 3) dense clumps with $Z \sim 10^{-5} Z_\odot$ and a metal-rich chimney-like cavity, whose size is several 100 pc, are formed as a result of 100 SNe. These result imply that the metallicity of the second generation stars would be $Z \sim 10^{-5} Z_\odot$, and the environment to form metal-free stars in proto-galaxies quickly ($< 10^7$ yr) lost after the first burst of star formation. If the star formation efficiency in proto-galaxies is a few %, the proto-galactic gas clouds turn into stellar system of $M \sim 10^{5-6} M_\odot$ with $Z \sim 10^{-3}$ during several generation of star formation.

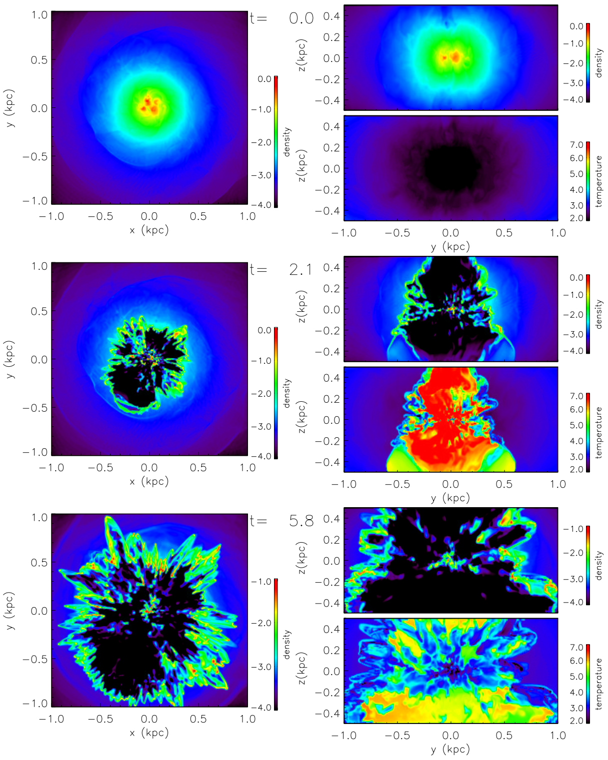

Figure 2: Density distribution of the initial condition ($t = 0$ Myr) and two snapshots ($t =$2.1 and 5.8 Myr) of a model with $N_{\rm SN} = 1000$. The left panels and the upper right panels are $x - y$ and $y - z$ cross sections of gaseous density, and the lower right panel is $y - z$ cross section of temperature. The density ($M_\odot$ pc^{-3}) and temperature (K) are log-scaled (Wada and Venkatesan 2002).

2.5 The Interstellar medium

The interstellar medium is also one of major topics investigated on the VPP5000. MHD turbulence in molecular clouds (Sugimoto, et al.), Origin of turbulence and formation of molecular clouds (Koyama, et al.), and gravity-driven turbulence in galactic disks (Wada) were studied.

Hiroshi Koyama (NAOJ) and his collaborators has studied on the thermal instability, using two and three-dimensional hydrodynamical and magneto-hydrodynamical simulations, taking into account radiative cooling, conduction and viscosity (Figure 3). They used 256^3 grid points, and found that the inhomogeneous structure and turbulent motion are generated due to the thermal instability, and then they are decayed. Interestingly, they found that the decaying process of the turbulent velocity field is strongly affected by the thermal conduction and viscosity.

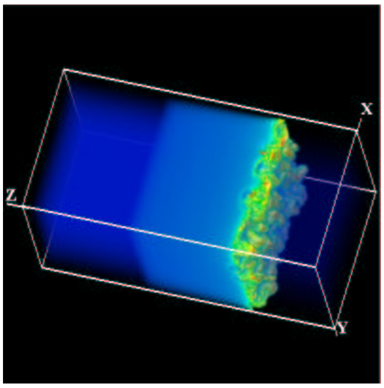

Figure 3: Three-dimensional magnetohydrodynamical simulation of the propagation of a shock wave into interstellar medium with radiative heating/cooling, thermal conduction, and physical viscosity. The initial weak magnetic field is in the x-direction and uniform. The magnetic pressure becomes comparable to the gas pressure in the post-shock region. Inutsuka and Koyama (2002).

I have studied the turbulence in the ISM from a different point of view (Wada, Gerhardt, & Norman 2002). Self-developed turbulence in a self-gravitating, rotating galactic gas disk was found, even if there is no explicit energy sources, such as supernova explosions. Analyzing the energy spectra of the velocity field, we found that the turbulence gains the energy on a scale of the gravitational instability, and then it inversely cascades towards larger scales. On a dynamical time scale, the energy spectra show a steady power-law shape. The energy source is the self-gravity of the gas and the galactic rotation.

2.6 Star formation and stars

Many studies are on-going in this field: formation of binary stars (Matsumoto et al.; see also Tomoaki Matsumot's paper in this volume), coalescence of neutron stars and gravitational waves by three-dimensional general relativistic simulations (Masaru Shibata, in this volume), and also by Ohara et al.; proto-stellar flare by Hayashi, M. et al.; collapse of rotating, magnetized clouds, & outflow by Tomisaka, K.; primordial star formation by Tsuribe.

Mitsuru Hayashi (NAOJ) and his collaborators have shown that a jet of hot plasma is created by the magnetic reconnection in the proto-stellar disk. The hot plasma (several keV) is created by the interaction between the magneto-sphere and surrounding accretion disk. In other words, the rotational energy of the accretion disk is converted to the magnetic field energy, and finally it is released as thermal energy of the flare. They claimed that their model well explains the x-ray flares observed in the proto-stars.

Kohji Tomisaka (NAOJ) has been working on collapse of magnetized molecular cloud cores (Tomisaka 2002). Using a well-designed multi-grid method, he succeeded in reproducing the outflow from the adiabatic core, as a result of the collapse of the molecular cloud. In the isothermal stage ($n \sim 10^{10}$ cm^{-3}), the cloud evolves similarly to that expected from the Larson-Penston self-similar solution and experiences a run-away collapse. However, after the central density exceeds the threshold, an accretion disk is formed around an adiabatic core. Just outside the core, an outflow is ejected by effect of the magnetic torque (magneto-centrifugal wind). Since ~ 10 % of the mass is ejected with almost all the angular momentum, the specific angular momentum of the proto-stellar core reduces to that observed in pre-main-sequence stars. Tomisaka claimed that this model could solve the long-standing problem on the angular momentum of the proto-stellar core.

2.7 Formation of planets and moon

Recently, theory of planet formation is greatly developed. A lot of important works has been done by using GRAPE. For example, formation of moon by a giant-impact (Takeda et al.), formation of proto-planet (Daisaka; Kokubo), and ring of Saturn (Ida et al.).

Here I introduce recent work on the giant-impact hypothesis of forming moon. The most plausible scenario to form our moon is so-called 'giant impact' between the proto-Earth and a Mars-size proto-planet. Figure 4 is my own three-dimensional hydrodynamical simulation of the giant impact process. 512^3 Euler grid cells are used. The proto-planet is completely destroyed by the collision, and a halo of debris is formed around the earth. Using GRAPE families, Eiichiro Kokubo (NAOJ) and his collaborators have revealed that a moon is formed from the debris just outside the Roche radius for about one month (Kokubo et al. 2000; Takeda and Ida 2001).

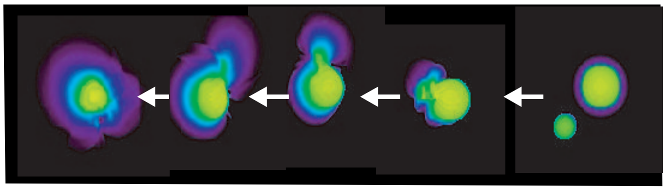

Figure 4: The giant impact simulated by 3-D hydrodynamical simulations using AUSM (Advection Upstream Splitting Method). The color represents density (Wada et al. in preparation)

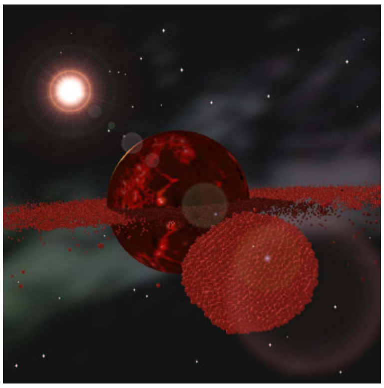

Figure 5: Formation of the moon. Courtesy by T. Takeda (NAOJ)

3 Concluding Remarks

The supercomputer system and facilities of the Astronomical Data Analysis Center (ADAC) of the National Astronomical Observatory of Japan is open for researchers (faculty, postdocs, and students) who are *official members of universities/institutes in Japan.* Any researchers in the world can apply their proposals on astrophysics and related fields. The proposals can be written in English. The primary investigator should be a faculty member or postdoc in Japanese institute. In fact, several researchers from other countries used the system last year.

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