21aD2-2

Generation of Magnetohydrodynamic, Turbulence behind Astrophysical Shock Waves
衝撃波による星間磁気乱流の生成と天体現象への応用

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The interstellar medium, whose dynamics can be described by magneto-hydrodynamics, is a quite dynamical medium because of frequent supernova explosions that cause strong shock waves. In this contribution, we show that the interaction between a young supernova shock wave and realistic two-phase interstellar medium induces the Richtmyer-Meshkov type instability that eventually creates turbulence behind the shock wave. The induced turbulence amplifies magnetic field and consequently brightens synchrotron radiation in young supernova remnants. We also show the detailed comparison between the prediction obtained from the results of our simulations and observations by using X-ray space telescopes.

1. Basics of the Interstellar medium

The interstellar medium (ISM) is an open system where radiative cooling and heating are effective with the timescale of 1 Myr, since the ISM is usually optically thin. The major cooling mechanism is thermally excited, fine structure line emissions by heavy elements such as carbon and oxygen atoms, and the major heating mechanism is the photoelectric heating by interstellar dusts such as polycyclic aromatic hydrocarbons (PAHs), whose energy source is background ultraviolet radiation from stars [1].

In Figure 1, we show the equilibrium state between the cooling and heating in the typical ISM. We see that there are two roughly isothermal equilibrium branches at $T \sim 100$ K and $T \sim 8{,}000$ K. A gas in the colder phase is called cold neutral medium (CNM), and that in the hotter phase is called warm neutral medium (WNM). These two phases are known to be stable against linear perturbations, while the branch that connects the two phases is unstable with respect to isobaric perturbations [2, 3]. Thus, under the typical thermal pressure in the ISM ($p/k_B \sim 4{,}000$ K cm^{-3}), both the CNM and WNM can coexist, indicating that the ISM is a quite inhomogeneous medium.

In Figure 2, by using three-dimensional magneto hydrodynamics (MHD) simulations, we show the density structure of the two-phase ISM created as a consequence of the thermal instability. The color bar indicates gas density that ranges from $n \sim 1$ cm^{-3} for the WNM to $n \sim 100$ cm^{-3} for the CNM. The black lines represent magnetic fields whose initial strength is $B = 5$ μG. The corresponding plasma β is on the order of unity in both WNM and CNM.

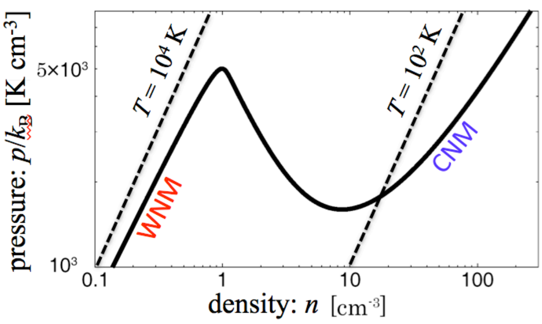


Figure 1: thermal equilibrium of the typical ISM

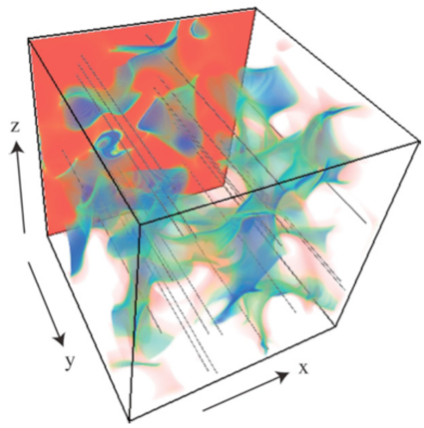
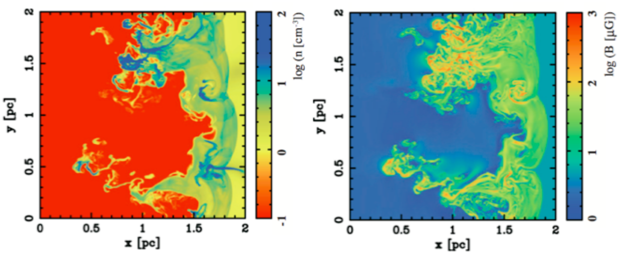


Figure 2: density structure of the two-phase ISM created as a consequence of the thermal instability. Blue regions correspond to the CNM and other regions to the WNM (taken from reference [11]).

2. Shock-cloud Interaction

In the ISM, supernova explosion (SNE) happens roughly once per a hundred years, and a strong shock wave induced by the SNE sweeps the ISM.

Figure3: 2D slices of the density (left) and magnetic field



(right) structures as a consequence of the interaction between a shock wave and two-phase ISM.

Supernova remnants (SNRs), which are composed of ejected stellar materials and shock compressed ISM, are astrophysically very interesting objects, because they accelerate particles by the so-called diffusive shock acceleration (DSA) mechanism [4], and show high-energy non-thermal emissions such as the synchrotron emission, the inverse Compton emission, the pion decay gamma-ray emission and so on [5, 6].

Until recently, theoretical studies of the SNRs have been done by assuming uniform ISM. However, as we have shown in the previous section, the ISM is an intrinsically inhomogeneous medium, and thus we should study SNR shock propagation in such a realistic medium.

A pioneering work is done by Giacalone & Jokipii (2008) who studied shock propagation through an inhomogeneous medium with Kolmogorov -like density power spectrum [7]. They found that the Richtmyer-Meshkov type instability induced by shock-density fluctuation interactions creates turbulence behind the shock, and the induced turbulence amplifies magnetic field through the stretching of the magnetic field lines. Inoue, Yamazaki & Inutuska (2009, 2010) and Inoue et al. (2012) upgraded the preshock ISM to the realistic two-phase medium, and performed 3D MHD simulations. They found that the shock-cloud interactions create strong transonic turbulence, and the magnetic fields are amplified intensively up to 1 mG in particular in the vicinity of the shocked clouds [8-10]. In Figure 3, we show 2D slices of the density (left) and magnetic field (right) structures.

3. Comparison with Observations

Observations by using the Chandra space X-ray telescope suggested that there are strong 1 mG magnetic fields in some young SNRs, while origin of them were puzzling [11]. Our simulations predicts that strong magnetic field should be observed in the vicinity of the shocked cloud, roughly 0.1 pc away from the cloud. Recent observations by using the Suzaku space X-ray telescope revealed that such a local small-scale anti-correlation between the shocked clouds and bright synchrotron emission regions is indeed ubiquitous in the SNR; RX J1713.7-3946 [12].

The above observations suggest that shock-cloud interaction indeed happens at least in SNR; RX J1713.7-3946, indicating that the gamma-ray emissions from this SNR would be hadronic pion decay emissions [13].

Acknowledgments

Numerical computations were carried out on XC30 system at the Center for Computational Astrophysics (CfCA) of National Astronomical Observatory of Japan, and in part on K computer at the RIKEN Advanced Institute for Computational Science (No. hp120087). This work is supported by Grant-in-aids from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan (23740154, 26287030).

References

[1] L. Spitzer: *Physical Processes in the Interstellar Medium* (New York: Wiley, 1978).
[2] Field, G. B. 1965, ApJ, 142, 531.
[3] Field, G. B., Goldsmith, D. W., & Habing, H. J. 1969, ApJ, 155, L149.
[4] Blandford, R. D., & Eichler, D. 1987, Phys. Rep., 154, 1.
[5] Koyama, K., Petre, R., Gotthelf, E. V., et al. 1995, Nature, 378, 255.
[6] Aharonian, F. A., Buckley, J., Kifune, T., & Sinnis, G. 2008, Rep. Prog. Phys., 71, 096901.
[7] Giacalone, J., & Jokipii, J. R. 2007, ApJ, 663, L41.
[8] Inoue, T., Yamazaki, R., & Inutsuka, S. 2009, ApJ, 695, 825.
[9] Inoue, T., Yamazaki, R., & Inutsuka, S. 2010, ApJ, 723, L108
[10]Inoue, T., Yamazaki, R., Inutsuka, S., & Fukui, Y. 2012, ApJ, 744, 71
[11]Uchiyama, Y., Aharonian, F. A., Tanaka, T., Takahashi, T., & Maeda, Y. 2007, Nature, 449, 576
[12]Sano, H., Tanaka, T., Torii, K. et al. 2013, ApJ, 778, 59.
[13]Fukui, Y., Sano, H., Sato, J. et al. 2012, ApJ, 746, 82