§2. Clarification of Magnetohydrodynamics Phenomenon of the Sun and Astronomical Objects

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The solar corona is filled with explosive phenomenon, such as flares, that are caused by a magnetic reconnection. The understanding of the physical processes behind this is a key problem in plasma physics. In this study, we investigate the magnetic reconnection involved in jets and solar flares, the propagation of the solar wind and magnetar flares, with the aim of clarifying the magnetohydrodynamics phenomenon occurring in different stellar bodies and on different scales.

i) Three dimensional MHD simulations of a solar flare Magnetic reconnection is a process in which the magnetic energy is converted into kinetic and thermal energy, and is widely believed to play a fundamental role in triggering solar flares. However, the fundamental physical processes have not been clearly explained, and it is still unknown as to what determines the energy release rate in flares. The answer is clearly related to the rate of magnetic reconnection, so to identify the conditions under which fast magnetic reconnection occurs is important. Observational results suggests a positive correlation between the velocity of the plasmoid ejected from a flare and the reconnection rate, suggesting a feed back mechanism between the two (plasmoid induced reconnection model). Until now there have been no MHD simulations performed to examine the plasmoid-induced reconnection model, which will allow an investigation of the correlation between the plasmoid velocity and the reconnection rate. In this study, we performed a series of MHD simulations of a solar flare, where the parameters related to resistivity and plasmoid velocity were changed to investigate the relationship between these two quantities. As a result of the simulations, we showed that the reconnection rate (i.e., inflow speed) and the plasmoid velocity are closely related to each other. This result is consistent with observations supporting the plasmoid-induced reconnection model of impulsive flares.

ii) Comparison between Hinode observation and magnetohydrodynamic simulation: Evidence of Magnetic reconnection and propagating Alfven wave associated with a Giant chromospheric jet. We analyzed a chromospheric jet observed with the Solar Optical Telescope (SOT) on board Hinode and compared it with our simulation results from a 2-dimensional MHD simulation. We initially assumed an oblique magnetic field in the solar corona and the flux tube just below the photosphere. The flux tube emerges into the corona through the Parker instability and reconnects with the oblique coronal field. Figure 2 shows the comparison between Hinode observation and MHD simulation results. It is clear that the simulation has accurately reproduced the observed jet. In the Hinode observation, we found a propagating Alfven waves associated with reconnection, there were also reproduced by our simulations. The wave energy is estimated to be sufficient for coronal heating, suggesting that reconnection contribute to coronal heating and solar wind acceleration.

iii) Relativistic Magnetohydrodynamics Simulations of Magnetar Outflows This is the first MHD simulation of a magnetar flare. Initially, we assume a hydrostatic circumsteller medium with a density $\rho(r) \propto r^{-\alpha}$ and a dipole magnetic field. An azimuthal shearing motion is also assumed around the equatorial surface, which generates the azimuthal component of the magnetic field. The subsequent evolution was simulated numerically. It is found that the magnetic pressure due to the azimuthal component of the magnetic field initiates an expanding outflow and a strong shock propagates through the circumstellar medium in connection with the expanding magnetic outflow. The shock wave dynamics were found to depend on the value of α. In the case where $\alpha < \alpha_{\rm crit} = 5$, the shock velocity $v_{\rm sh}$ depends on the strength of the initial dipole field ($B_{\rm dipole}$) and is described by a simple scaling relation $v_{\rm sh} \propto {B_{\rm dipole}}^{0.5}$. In this case, the accelerating force is the magnetic pressure due to azimuthal component of the magnetic field created by the shearing motion. When $\alpha > \alpha_{\rm crit}$, the outflow-driven shock can be accelerated self-similarly to reach relativistic velocity. The self similar relation is $\Gamma_{\rm sh} \propto r_{\rm sh}$. This results from the steep initial density profile when $\alpha > \alpha_{\rm crit}$, hence this is a hydrodynamic process.

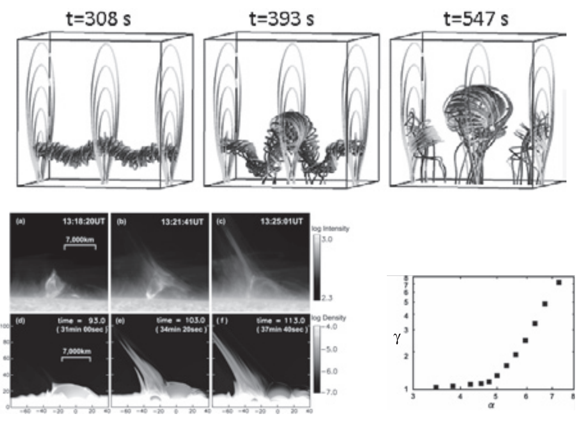

Fig. 1: (Top)Time evolution of a flux rope. (Bottom-left)Comparison between Hinode observation of a chromospheric jet and our simulation results. (Bottom-right) The relation between the initial density profile of circumstellar medium (e.g., index α) and the shock velocity at $r = 150R_{\rm NS}$ on the equatorial plane. The shock is strongly accelerated to reach relativistic velocity when α is greater than ~ 5.