Magnetohydrodynamic Simulations of Hard X-Ray Emission and Mass Outflows from Protostars
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Abstract
We carried out 2.5 dimensional magnetohydrodynamic (MHD) simulations of the magnetic interaction between a protostar and its surrounding disk. The results show that high-velocity and high-temperature plasma flows can be created via magnetic reconnection. In our model which can explain protostellar flares and mass outflows both qualitatively and quantitatively, magnetic reconnection plays an essential role in heating the plasmas. We analyse the one-dimensional distribution across the shock around the reconnection site to clarify the heating mechanism in protostellar flares. Around the reconnection point, we found two peaks of peaks of toroidal current density and a pressure increase with decreasing the magnetic field strength, indicating that these shocks are slow-mode shocks.

1 Introduction
The ASCA satellite detected hard X-ray emissions from protostars (Koyama et al. 1994, 1996a, 1996b). The light curves of the flares of protostars are quite similar to those of the Solar flares. But the luminosity is much larger than the Solar flares. The temperature is more than several keV and the size of the magnetic loops is estimated to be larger than the radius of the central star. Recently Yokoyama and Shibata (1999) showed scaling laws between electron temperature and emission measure in magnetic reconnection events. The relation between the electron temperature and emission measure of protostellar flares detected by ASCA supports the above scaling laws and suggests the intimate relation between protostellar flares and magnetic reconnections.

Hayashi et al. (1996) carried out 2.5D magnetohydrodynamics (MHD) simulations of the magnetic interaction between the dipolar magnetic fields of the central star and its surrounding accretion disk. A current sheet is formed inside the expanding magnetic loops via the magnetic interaction. In the presence of the electric resistivity, magnetic reconnection occurs. High temperature and high velocity plasma flows are created by the magnetic reconnection event. The results of the simulation above shows that the temperature of the outflowing plasma corresponds to keV and the velocity of it corresponds to several hundred km/s. According to these simulations they concluded that the model can explain the protostellar flares both qualitatively and quantitatively.

In the Petschek model of magnetic reconnection, wave heats and accelerates high temperature and high velocity plasma flows in magnetic reconnection event. We investigate the physical structure around magnetic reconnection site and show that the structure reflects the formation of MHD slow-mode shocks.

2 2.5D MHD Simulations of Protostellar Flares
Figure 1 shows the typical results of the simulation of protostellar flares. The dipolar magnetic fields connecting the central star and its surrounding disk are twisted by the rotation of the disk. The accumulation of the twist makes magnetic loops expand and the expanding loops approach open field configuration. A current sheet is formed inside the expanding loops. The presence of the electric resistivity leads to magnetic reconnection in the current sheet. As the magnetic reconnection proceeds, postflare loops are formed.

Solid curves in Figure 1 show the magnetic field lines. The color scale shows the temperature. The arrows show velocity vectors.

The magnetic field lines near the disk have small angle with respect to the equatorial plane. This configuration is favorable for the appearance of magnetocentrifugal winds from accretion disks.

The terminal speed of the wind is the order of the Keplerian rotation speed at the footpoint of the field lines on the disk. Since the density is high, the mass outflow rate of the cold disk wind is several times larger than that of the hot plasma jet driven by the reconnection.

3 One-dimensional Distribution of Physical Quantities around Magnetic Reconnection Site
We measured one-dimensional distribution of physical quantities along the black line shown in Figure 2 across the plasma outflows around the magnetic reconnection point. Figure 3 shows the results. Toroidal electric current distribution along the black line in Figure 2 shows two peaks. The peaks correspond to the discontinuity of the strength of electric currents and magnetic fields. This is one of the characteristic properties of MHD slow-mode shock.

Figure 1: Typical results of the simulation of protostellar flare.

Figure 2: The distribution of physical quantities are measured along the black line across the plasma outflows near the reconnection site. White line shows the line normal to the black one above and shows the almost the same direction as the plasma outflows.
The temperature distribution shows that the temperature between the peaks above (slow-mode shocks) is higher than the other parts. After reconnection accelerated bulk motion around magnetic reconnection site forms shocks and heats the plasmas. The temperature distribution also shows features characteristic of slow-mode shock.

In Figure 3, $V_r$ and $V_z$ change their signs along the black line in Figure 2 and $V_r$ shows their peaks at the region between the two peaks of toroidal electric current. This situation shows that magnetic tension accelerates plasmas around the magnetic neutral point and the velocity of the outflowing plasma corresponds to the Alfvénic velocity.

Along the line shown in Figure 2, magnetic pressure is lower in the region between the slow-mode shocks. On the other hand, the thermal pressure is higher in the region. The total pressure is almost in equilibrium around slow-mode shocks.

4 Summary and Discussion
Our model can explain both the hard X-ray emission and bipolar mass outflows from protostars.

The structure around magnetic reconnection site is investigated. Two peaks in the one-dimensional distribution of toroidal electric current and the temperature shows the characteristic properties of MHD slow-mode shock formation and heating by the shock.

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References
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