

X-Ray Flares and Outflows Driven by Magnetic Interaction Between a Protostar and its Surrounding Disk

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Abstract. Here we present a model of hard X-ray flares and hot plasma outflows (optical jets) observed in protostars. Assuming that the dipole magnetic field of a protostar threads the protostellar disk, we carried out 2.5-dimensional magnetohydrodynamic (MHD) simulations of the disk-star interaction. The closed magnetic loops connecting the central star and the disk are twisted by the rotation of the disk. In the presence of resistivity, magnetic reconnection takes place in the current sheet formed inside the expanding loops. Hot, outgoing plasmoid and post flare loops are formed as a result of the reconnection. Numerical results are consistent with the observed plasma temperature ($10^7 - 10^8\text{K}$), the length of the flaring loop ($10^{11} - 10^{12}\text{cm}$), and the speed of optical jets ($200 - 400 \text{ km s}^{-1}$).

1. Introduction

By using ASCA, Koyama et al. (1996) carried out a systematic survey of hard X-ray sources in molecular clouds and revealed that protostars are strong hard X-ray emitting sources. Some of them show flare-like activities. Protostellar flares differ from solar flares in their total energy (10^{35-36} erg), size (several times the radius of protostar), and higher temperature (8keV). A possible driving source of protostellar flares is the disk rotating around a protostar.

Recently, Hayashi et al. (1996) carried out MHD simulations of protostellar flares by extending the model of solar flares associated with footpoint motions (e.g., Mikic & Linker 1994). We assumed that the dipole magnetic field of the protostar threads the protostellar disk.

Since the disk continuously injects helicity into the magnetosphere, we expect magnetic nonequilibrium and resulting magnetic reconnection similar to those proposed for solar flares. In the following, we present numerical results of the disk-star magnetic interaction.

2. Numerical Models & Results

We solve the resistive MHD equations in cylindrical coordinate by applying a modified Lax-Wendroff scheme with artificial viscosity. Figure 1 shows a typical result. Magnetic field lines connecting the central star and the disk are twisted by the rotation of the disk. As the magnetic twist accumulates, the magnetic loops expand quasi-statically in the early stage but later, they expand dynamically. Magnetic reconnection takes place in the current sheet formed inside the expanding loops. Figure 2 shows various energies in the hot ($T > 1.2 T_0$) component and the total magnetic energy. Released magnetic energy goes into the thermal and kinetic energy of the outgoing plasmas.

3. Summary & Discussion

We demonstrated that the dipole magnetic fields of the protostar can become partially open by imposed twists within one rotation of the disk. We also showed that hot plasmoids are ejected in bipolar directions with velocity 2–5 times the Keplerian rotation speed (v_{K0}) around the inner edge of the disk. Plasma heating occurs both by Joule heating in the current sheet and by shock waves created by magnetic reconnection. The plasma temperature corresponding to a reconnection flow speed (\sim Alfvén speed $\sim 2 - 5v_{K0}$, where v_{K0} is the Keplerian velocity at unit radius) can be $10^7 - 10^8$ K, consistent with the observed spectrum which extends up to 10 keV. The size of the flaring loop is several times the stellar radius. The speed of the hot plasma outflow (200 – 400 km/s) is close to that of optical jets. Our reconnection model can explain both hard X-ray flares and mass outflows in protostars.

References

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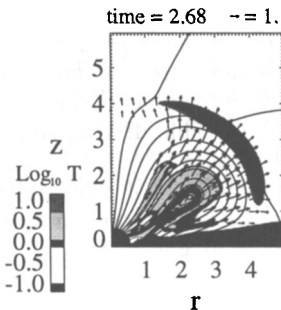


Figure 1. A typical result of the numerical simulation. Grey scales show temperature. Solid curves show magnetic field lines. Arrows depict velocity vectors.

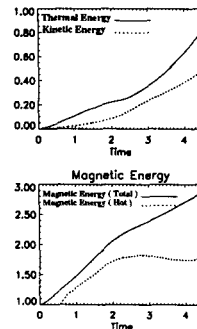


Figure 2. Time history of various energies.