

# Accretion shocks in the laboratory: Design of an experiment to study star formation



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## ABSTRACT

We present the design of a laboratory–astrophysics experiment to study magnetospheric accretion relevant to young, pre–main–sequence stars. Spectra of young stars show evidence of hotspots created when streams of accreting material impact the surface of the star and create shocks. The structures that form during this process are poorly understood, as the surfaces of young stars cannot be spatially resolved. Our experiment would create a scaled “accretion shock” at a major (several kJ) laser facility. The experiment drives a plasma jet (the “accretion stream”) into a solid block (the “stellar surface”), in the presence of a parallel magnetic field analogous to the star’s local field. We show that this experiment is well–scaled when the incoming jet has  $\rho \sim 10^{-6}–10^{-5} \text{ g cm}^{-3}$  and  $u \sim 100–200 \text{ km s}^{-1}$  in an imposed field of  $B \sim 10 \text{ T}$ . Such an experiment would represent an average accretion stream onto a pre–main sequence star with  $B \sim 700 \text{ G}$ .

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## 1. Introduction

Accretion shocks form when material from an accretion disk impacts at the surface of the object growing at its center. The object’s magnetic field governs the interaction between the two through what is called magnetospheric accretion. Originally proposed by Königl [22], who extended the compact object work of Ghosh and Lamb [8,9] to T Tauri stars (low–mass pre–main–sequence stars), the magnetospheric accretion model has material from the accretion disk lifted out of the plane of the disk and “funneled” along the star’s magnetic field lines to its surface. Today, there is ample evidence that magnetospheric accretion occurs on T Tauri stars (see Bouvier et al. [3] and references therein). There is also evidence of magnetospheric accretion occurring on T Tauri stars’ more massive counterpart, Herbig Ae/Be stars [12,29,31].

When the supersonic material impacts the surface of the young star—T Tauri or Herbig Ae/Be—an accretion shock hot enough to emit soft X–rays ( $T \sim 10^6–10^7 \text{ K}$ ) forms. There is ample evidence of this in the X–ray spectra of T Tauri stars [1,2,4,13,21,38,42,43], and evidence is growing that at least some Herbig Ae/Be stars exhibit X–ray–emitting accretion shocks as well [6,10,44,45].

The mass accretion rate of a star ( $\dot{M}$ , usually on the order of  $10^{-8} M_{\odot}$  per year) can be determined from the effect that these X–ray emitting accretion shocks have on the star’s spectrum. The X–rays heat the surrounding photosphere, producing spots of hot

plasma [5]. Compared to a similar non–accreting star, an accreting star ought to have excess emission in the optical and UV due to these spots, and its accretion rate can be calculated from the amount of excess emission [15,16,30,33,46].

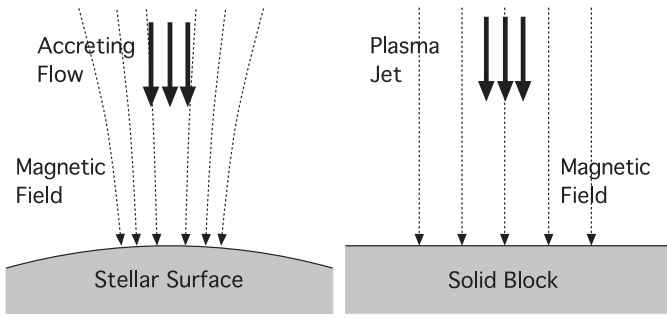
However, these accretion rate calculations are only as good as the understanding of accretion shock structure behind them. Because the surfaces of young stars cannot be spatially resolved, the structure of accretion shocks has not been directly studied. For example, do accretion shocks penetrate the star’s photosphere, potentially hiding much of the accretion shock’s energy from observers? Or, do accretion shocks create large “splashes” when they hit the surface of the star, making it appear the shock covers more surface area than it actually does? Either of these scenarios would potentially change the calculated accretion rate significantly.

Simulations of accretion shocks have largely served to underscore how complicated and inherently three–dimensional the systems are. Three–dimensional simulations by Romanova et al. [39] predict that accretion hotspots should be inhomogenous and irregularly shaped. Likewise, simulations by Orlando et al. [34] found that T Tauri accretion shocks can produce violent splash zones, particularly when the magnetic field strength is too low to contain the accretion shock.

To this end, we propose our design of an experiment to produce a scaled laboratory version of an accretion shock. We would use a high–energy (several kJ) laser to make a supersonic plasma jet (the “accretion stream”) and drive it into a solid block (the “stellar surface”) in the presence of an imposed magnetic field. Section 2 establishes the connection between magnetic accretion on a

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**Fig. 1.** In the astrophysical system (left), accreting plasma falls to the stellar surface along magnetic field lines (depicted here as a magnetic dipole at the pole of the star). In the lab experiment (right), a plasma jet collides with a solid block with a parallel background magnetic field.

pre-main-sequence star and the laboratory experiment and lays out the plasma parameters that we must seek to have a well-scaled experiment. Section 3 discusses design considerations of our experiment, and Section 4 presents our conclusions.

## 2. Experimental goals

### 2.1. Basic configuration

Laboratory astrophysics offers the ability to probe scaled astrophysical systems in an experimental setting [36,37,41]. Examples of such experimental campaigns include the work of Kuranz et al. [25], who created Rayleigh–Taylor blast waves relevant to supernovae remnants; the work of Hartigan et al. [14], who created deflected supersonic jets relevant to Herbig–Harro objects; and the work of Krauland et al. [23], who created reverse shocks relevant to interacting binaries.

Our astrophysical system, an accreting young star, consists of (1) accreting material which collides with (2) the surface of the growing star in the presence of (3) a magnetic field parallel to the material's flow and perpendicular to the star's surface. Creating a scaled version of this system means translating these three into the lab, as seen in Fig. 1. In the experiment, we drive a plasma jet (the “accreting material”) into a solid block (the “stellar surface”) with an imposed magnetic field.

### 2.2. Dimensionless numbers

Astrophysical systems can never be scaled and reproduced perfectly in the lab. Having a worthwhile experiment, therefore, hinges on discerning which physical processes are most important and translating them into an experiment appropriately. Ryutov et al. [41] lays out a theoretical basis for doing so: one must ensure that dimensionless numbers (for example, Reynolds number) that define the system are at least in similar regimes.

There are five dimensionless numbers that concern the accretion shock experiment. The first two determine whether a shock can form in the first place, the second two determine the role of magnetic fields in the experiment, and the last is the Reynolds number, which relates the importance of viscosity in the system. The scaling criteria we impose are as follows:

1.  $\mathcal{M} > 1$ .  $\mathcal{M}$  is the Mach number, the ratio of the flow velocity of the jet to the speed of sound inside the jet; we need a supersonic jet in order to have a shock. Sound speed was calculated according to

$$c_s = 9.79 \times 10^5 \sqrt{\frac{\gamma(Z+1)T_e}{A}} \text{ cm s}^{-1}, \quad (1)$$

where  $\gamma$  is the adiabatic index,  $Z$  is the ionizations,  $T_e$  is the temperature in eV, and  $A$  is the atomic mass in proton masses.

2.  $\lambda_{\text{MFP}} < L$ .  $\lambda_{\text{MFP}}$  the ion-ion mean free path inside the plasma and  $L$  is the overall lengthscale of the experiment. We impose  $\lambda_{\text{MFP}} < L$  in order to observe a shock in the experiment. Mean free path was calculated according to

$$\lambda_{\text{MFP}} = \frac{1}{n_i \sigma_{90}^{ii} 4 \ln \Lambda_{ii}}, \quad (2)$$

where  $n_i$  is the ion density,  $\sigma_{90}^{ii}$  is the  $90^\circ$  cross-section, and  $\ln \Lambda_{ii}$  is the ion-ion Coulomb lambda. The  $90^\circ$  cross-section was calculated according to

$$\sigma_{90}^{ii} = \frac{\pi e^4 Z^4}{m_i u^4}, \quad (3)$$

where  $e$  is the charge of an electron,  $Z$  is the average ionization,  $m_i$  is the ion mass, and  $u$  is the relevant velocity (in this case the flow velocity).

This criterion ( $\lambda_{\text{MFP}} < L$ ) also ensures that our plasma is collisional. Park et al. [35] give the condition for a collisionless plasma as  $L \ll \lambda_{\text{MFP}}$ , where  $\lambda_{\text{MFP}}$  is the ion-ion MFP of the heaviest ion species, so a plasma with  $\lambda_{\text{MFP}} < L$  would be collisional.

3.  $\ell_M < L$ .  $\ell_M$  is the magnetic diffusion lengthscale, and  $L$  is the overall lengthscale of the experiment. We impose  $\ell_M < L$  in order to ensure the magnetic field does not diffuse away during the experiment. To find  $\ell_M$ , we consider a generic diffusion equation,

$$\frac{\partial \phi}{\partial t} = D \nabla^2 \phi, \quad (4)$$

where  $\phi$  is some generic diffusing quantity and  $D$  is the generic diffusion constant with units  $L^2 T^{-1}$ . Applying unit analysis we find

$$\frac{\phi}{\tau} = D \frac{\phi}{\ell^2}, \quad (5)$$

where  $\tau$  is the timescale of interest and  $\ell$  is the diffusion length over  $\tau$ . This yields  $\ell = \sqrt{D\tau}$ .

In the case of magnetic diffusion, the diffusion constant is the magnetic diffusivity in the post-shock region,  $\nu_M$ , and the timescale of interest is  $L/u$ , the dynamic timescale. The magnetic diffusivity is,

$$\nu_M = \frac{c^2 \eta_\perp}{4\pi}, \quad (6)$$

where  $c$  is the speed of light, and  $\eta_\perp$  is the transverse Spitzer resistivity. The expression for transverse Spitzer resistivity is taken from the *Plasma Formulary*, [18]:

$$\eta_\perp = 1.15 \times 10^{-14} \frac{Z \ln \Lambda}{T_e^{3/2}} \text{ sec}, \quad (7)$$

where  $Z$  is the ionization,  $\ln \Lambda$  is the Coulomb logarithm, and  $T_e$  is the electron temperature in eV.

Altogether this yields

$$\ell_M = \sqrt{\frac{\nu_M L}{u}} = \sqrt{\frac{c^2 \eta_\perp L}{4\pi u}} \quad (8)$$

4.  $0.1 < \beta_{\text{ram}} < 10$ .  $\beta_{\text{ram}}$  is the ratio of ram pressure of the jet to the magnetic pressure of the field

$$\beta_{\text{ram}} = \frac{\rho u^2}{B^2/8\pi}, \quad (9)$$

where  $B$  is magnetic field strength.

A typical accreting young star system with a magnetic field of 1000 G will have  $\beta_{\text{ram}} \sim 1$ . The range of acceptable  $\beta_{\text{ram}}$  imposed here corresponds to magnetic field of 3000 G (low  $\beta_{\text{ram}}$ ) to 300 G (high  $\beta_{\text{ram}}$ ).

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