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# Viscous Dissipation in the Galactic Center Region

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**Abstract.** For more than two decades, X-ray observations have revealed strong iron line emission from the central few hundred parsecs of the Galaxy. We have recently suggested that, hydrogen having escaped from the Galactic potential, it might be a helium plasma. But this leaves open the problem of heating the plasma. Here we present a possible heating mechanism in which the gravitational and kinetic energy of cold molecular clouds are dissipated in the surrounding plasma by the strong viscosity acting there. The possible existence of a vertical magnetic field in this region has a strong influence on the viscous properties and is fully taken into account. The MHD wakes of the moving clouds are analyzed in detail and it is shown that its Alfvén component can be responsible for an energy dissipation strong enough to drive efficient heating.

## 1. Introduction

Whereas the Galactic Center region is strongly obscured at optical wavelengths, it is responsible for intense X-ray emission. This emission is strongly peaked in the 300 first parsecs [1]. Whereas the soft part of the X-ray spectrum (between 1 and 5 keV) has been successfully identified as originating in supernova remnants, the medium responsible for hard emission (between 5 and 10 keV) remains uncertain. The continuum and the two strong  $K\alpha$  lines from H-like and He-like iron at 6.7 and 6.9 keV cannot originate in the  $\sim 1$  keV plasma of SNRs. Although many hypotheses have been suggested to explain the hard emission, only two of them are still consistent with the most recent observations with Chandra [2], XMM and Suzaku (see the contribution by K. Koyama). The hard emission could originate in hot plasma from numerous discrete point sources that are not resolved by current observations, mostly Cataclysmic Variables [3]. However from what can be inferred from existing observations, it seems there are not enough of them by a factor of a few to account for the X-ray luminosity in the central region. Also, this emission could originate in a truly diffuse plasma whose temperature must be 8 keV to account for the very ionized iron lines. It has long been noted that the temperature is too high for an ordinary interstellar plasma to be bound by the gravitational potential, so the plasma should outflow quickly from the central region, requiring an unreasonable power for its heating. However, we have recently pointed out that this plasma is weakly collisional, the collision time for protons being longer than their escape time. Protons could thus escape without bringing out heavier ions, which are gravitationally bound. This selective evaporation, similar to that in planetary atmospheres, would naturally leave a heavy plasma, mostly composed by helium, confined in the Galactic plane [4]. If the X-ray emission originates in a bound plasma, the energetic requirements

are much more reasonable. If there is no other cooling mechanism, the heating only needs to balance the X-ray luminosity in the entire region, e.g.  $L \approx 4. \times 10^{37}$  erg s<sup>-1</sup>. Still no precise mechanism has been proposed for this heating.

Here we present such a mechanism. It uses the gravitational and kinetic energy of the cold molecular clouds flowing in this region. The intense radio and far-infrared emission observed in the Central Molecular Zone (CMZ, [7]), extending out to about 150 pc, reveals that the molecular content is condensed in cold (70K) and dense ( $10^3$ - $10^4$  cm<sup>-3</sup>) molecular clouds. Numerous surveys have given a knowledge of their statistical properties [8, for instance]: there are at least 100 of them in the CMZ and their typical size is about 10 pc. In a first approximation, they move on very elongated orbits [9, 7] but the velocity dispersion is large and they can have up to 130 km<sup>-1</sup> forbidden velocities. Whether or not the hot gas rotates at some Keplerian velocity, most of the clouds must flow relative to it, with a typical velocity of 100 km s<sup>-1</sup> [10]. The orbital and dispersion velocities represent a huge reservoir of kinetic and gravitational energy that can be tapped to heat the surrounding plasma.

The mechanism we have investigated dissipates this energy thanks to the strong viscosity of the hot plasma. However, observations of many magnetized non-thermal filaments [5, 6] seem to trace a pervasive and vertical magnetic field [7]. Its intensity is strongly debated but ranges between 10  $\mu$ G and a few mG. Such a field modifies dramatically the viscous properties of the plasma, namely it strongly inhibits its efficiency.

In section 2, we briefly review the viscous properties of a 8 keV plasma. Then in section 3, we present the inviscid MHD wake of clouds moving in a surrounding magnetized plasma. The way the viscosity can act on this wake and dissipate energy is detailed in section 4 and the overall efficiency is eventually discussed in section 5.

## 2. The Braginskii viscosity

The viscous coefficient of a non-magnetized 8 keV plasma is [11]:

$$\eta_0 = 630 \text{ g cm}^{-1}\text{s}^{-1} \left( \frac{k_B T}{8 \text{ keV}} \right)^{5/2} \quad (1)$$

Because of its high temperature, the diffuse plasma in the Galactic Center might be very viscous if not magnetized. For instance, the flow past a cloud would lead to Reynolds numbers of:  $\mathcal{R}_e \approx 10^{-2}$ .

However, magnetized plasmas have different properties [12]. The general viscosity can be described as the sum of two kinds of viscosity. The off-diagonal terms in the stress tensor are responsible for the usual *shear* viscosity proportional to terms in  $\partial_i v_j$ , e.g., to the shear of the velocity field. The diagonal terms are responsible for the *bulk* viscosity, proportional to terms in  $\partial_i v_i$ , e.g., to the compression of the fluid. For subsonic motion, the compression is weak:  $\partial_i v_i < \partial_i v_j$ , so that bulk viscosity is often neglected.

Any magnetic field makes this stress tensor anisotropic: in magnetized plasmas the diffusive properties are very different in the directions parallel and perpendicular to the local magnetic field. A significant magnetic field reduces the shear viscosity whereas it leaves bulk viscosity unchanged. Namely, off-diagonal terms scale with the diagonal ones as inverse powers of  $\Omega_c \tau$ , where  $\Omega_c$  is the cyclotron frequency and  $\tau$  is the Coulomb collision time. Even for the lowest estimates for the magnetic field intensity ( $B \sim 1 \mu$ G), the largest coefficient for the shear viscosity is divided by more than ten orders of magnitude compared to a non-magnetized situation:  $\Omega_c \tau \approx 10^{11}$ . As a result, the usual shear viscosity is fully inhibited and only bulk viscosity remains. The local dissipation caused by the bulk contribution is:

$$Q = \frac{\eta_0}{3} \left( \vec{\nabla} \cdot \vec{v} - 3 \partial_{\parallel} v_{\parallel} \right)^2 \quad (2)$$

where  $\parallel$  refers to the direction parallel to the field lines. The dissipation results from the compression  $\vec{\nabla} \cdot \vec{v}$  or from some velocity parallel to the field  $v_{\parallel}$ . At this point, it is not easy to estimate the dissipation efficiency. On the one hand, the viscous coefficient is large, because the temperature is high. On the other hand, the compression is weak, because the motion is subsonic. A precise estimate of the compression is required.

### 3. The wake of molecular clouds

In this section, we describe the inviscid wake of a moving molecular cloud. The compression in the wake is emphasized, since this is what drives the dissipation.

Since molecular clouds are ionized at least on their surface, they can be considered to a good approximation as conductors. The motion of such bodies moving in a magnetized plasma has already been investigated in different astrophysical conditions. From work on the motion of artificial satellites in the Earth's magnetosphere or the motion of Io in the Jovian magnetosphere, it is known that these bodies mostly excite Alfvén waves. These waves propagate along the field lines, carrying a strong energy flux [13, 14]. Other modes are also excited, but are likely to remain weak in amplitude [15, 16].

In a general manner, the wake of a molecular cloud moving in a magnetized plasma can be considered to be the sum of three components characteristic of the three MHD modes that can propagate in magnetized plasmas: the Alfvén and the slow and fast magnetosonic components. Because these modes have different propagation and polarization properties, the three components are spatially separated and are subject differently to bulk viscosity. The typical MHD wake is presented on figure 1a.

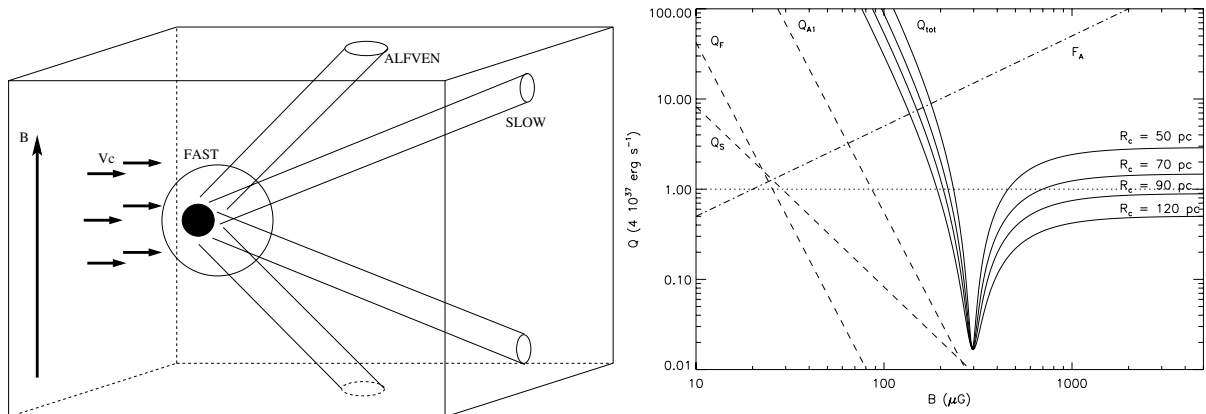
The Alfvén waves propagate along the field lines at the Alfvén velocity  $v_A$ . In a picture where the field is vertical and the cloud moves horizontally at  $v_c$ , the Alfvén perturbations excited on the cloud surface remain always localized along the Alfvén characteristics. They form a cylinder inclined of an angle  $\alpha_A = \tan^{-1}(v_c/v_A)$  from the vertical. As the motion of the clouds in the Galactic Center region is subalfvénic, these *Alfvén wings* are almost vertical. Alfvén waves are not compressible so that there is no density perturbation associated with their propagation. Also, in linear analysis, the velocity perturbation has no component parallel to the field. As a result, they cannot be linearly damped by bulk viscosity.

Most of the velocity perturbation resulting from the flow around the cloud is Alfvénic. However, other modes must also be excited. For instance, the non-linear analysis of the Alfvén wings shows that they drive a small net outflow of matter. To balance this outflow at the cloud surface, sonic perturbations must be associated with some net inflow onto the cloud.

The magnetosonic waves are compressible by nature, so that they are natural candidate for the dissipation. They have complicated propagation properties but for sake of simplicity, we assume that the field is super-equipartition ( $\beta > 100\mu G$ ). In this limit, the slow magnetosonic waves propagate along the field lines at the sound speed  $c_s$ , so that they can form a wing, exactly as Alfvén waves do; and fast magnetosonic waves propagate isotropically, so that their amplitude decays with the distance to the cloud because of geometrical effects and they remain localized in the cloud vicinity as usual sonic waves would do. No precise amplitude for the sonic components has been found analytically. However, upper estimates can be found. Based on the mass balance between the Alfvén and the slow components and on the properties of pure sonic waves in non magnetized plasmas, it can be shown that the amplitude of both the slow and fast perturbations remains very weak in comparison to the Alfvén one.

### 4. Dissipation

In this section, we analyze the effect of viscosity on each component of the wake. The dissipation is then summed over all the clouds in the entire central region and compared to the X-ray luminosity.



**Figure 1.** a) *Left panel:* The wake of a conducting molecular cloud moving in a magnetized plasma. b) *Right panel:* Alfvén flux  $F_A$  and dissipation rates in the different components of the wake, normalized to the X-ray luminosity.  $Q_s$  and  $Q_f$  are the rate in the slow and fast perturbation respectively.  $Q_{A1}$  is the dissipation rate in the non-linear Alfvén wing.  $Q_{tot}$  is the total dissipation dominated by the dissipation of the Alfvén wings in a curved field, for several curvature radii.

#### 4.1. The sonic components

As was explained earlier, the amplitude of the magnetosonic perturbations is weak, so that the overall associated dissipation is weak. On the one hand, the slow wing is conditioned by the non-linear properties of the Alfvén wing; on the other hand, the fast perturbation is governed by the cloud speed. In both cases, the compression goes as some power of  $v_c/v_A \ll 1$ . The strong magnetic field also inhibits the dissipation by bulk viscosity. The overall dissipation in the central region is plotted on figure 1b. For any value of the field intensity, the dissipation in the sonic components is insufficient to balance the radiative cooling. Only weak fields seem to permit an efficient heating, but in this limit, the assumption we have used to simplify the study of sonic waves fails.

#### 4.2. The Alfvén component

As we mentioned earlier that linear Alfvén wings are incompressible, so that they cannot be damped by the bulk viscosity. However, the energy flux carried away by these Alfvén waves is large:  $F_A = 2. \times 10^{38} \text{erg s}^{-1} (B/0.1 \text{ mG})$ . For the smallest estimates, this flux is comparable to the power needed to balance the radiative cooling and for the largest, it is more than 2 orders of magnitude larger! It is thus tempting to create a more realistic model that dissipates this available energy. There are many ways to damp Alfvén waves. Here, we present two of them.

First, as mentioned earlier, non-linear Alfvén wings involve a parallel velocity component, so that although they are incompressible, non-linear Alfvén waves can be dissipated by bulk viscosity (see eq. 2). Again, since the clouds' motions are subalfvénic, the non-linear terms are weak, so that only a small fraction of the Alfvén flux can be dissipated. However, for small fields ( $B < 100 \mu\text{G}$ ), this is enough to heat the plasma (see figure 1b).

Second, Alfvén waves are truly incompressible only in a perfectly straight magnetic field. Obviously, the field lines in the Galactic Center region are not straight, as can be inferred from the slight bending in most of the non-thermal filaments. In a curved geometry, Alfvén waves couple to slow magnetosonic waves and acquire a compressional component. They can thus be subject to bulk viscosity. Since the compression of these Alfvén waves relies basically on

geometrical effects, the compression is  $\vec{\nabla} \cdot \vec{v} \approx v_c/R_c$  where  $R_c$  is the local curvature radius. The heating efficiency is plotted on figure 1b.

## 5. Discussion and Conclusions

From the previous results, it can be concluded that the dissipation of the kinetic and gravitational energy of the clouds a) is dominant in the Alfvén wings, b) results mostly from the curvature of the magnetic field lines and c) is most efficient for  $B < 150 \mu\text{G}$  and  $B > 600 \mu\text{G}$ . With the typical estimates for the cloud number and size of  $n_c \approx 100$ ,  $r_c \approx 5 \text{ pc}$ , the plasma temperature and density of  $k_B T = 8 \text{ keV}$ ,  $n \approx 0.1 \text{ cm}^{-3}$ , the field curvature radius of  $R_c \approx 100 \text{ pc}$ , and within the expected range of field intensity, this dissipation is strong enough to balance the radiative cooling, allowing a temperature equilibrium.

One main assumption in this model is the pervasive and vertical nature of the magnetic field. This is most consistent with observational evidence, but strongly debated. A turbulent or horizontal field would probably give very different results and it is difficult to predict its impact on the dissipation rate. However, it is likely that the dissipation could be at least as efficient since the temperature would still guarantee a large coefficient for the bulk viscosity. In addition, as most of the energy leaves as Alfvén waves, and is only partially dissipated by bulk viscosity, the strong coupling between the compressible magnetosonic modes and the Alfvén ones in a tangled field would probably enhance the dissipation rate. Even if the Alfvén flux is weakly dissipated, it cannot leave the Galactic plane as in a straight field geometry and must remain in the plane until it is eventually dissipated.

Also, we have worked with the guideline that the hard emission originates in a hot diffuse plasma. As mentioned in the introduction, it might also come from unresolved discrete point sources. Presently, there is no observational evidence that permits one to discriminate between these two models. On the one hand, it seems that there are not enough point sources to account for the hard emission. On the other hand, until now there was no precise mechanism able to heat the plasma at the inferred temperature. Here we have presented such a mechanism, showing that the idea of a diffuse plasma in the Galactic Center is consistent with our current understanding of this region.

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