MHD ASPECTS OF GALACTIC CENTER PHYSICS

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ABSTRACT. This review addresses the question of MHD phenomena in the galactic center, which are expectedly important in view of the large value of the magnetic field. A physical similarity with other MHD environments where magnetic fields are dominated by a dense driver and dominate a more tenuous halo is recognized. Known physics rules this type of coupling. Most proposed MHD theories of the galactic center fit, at least partly, in this general frame. One of them views Sgr A and its environment up to 50pc as an active corona, similar to that of the sun, whose driver is some central accretion disk, which may (or may not) be the molecular ring. This unified picture is outlined and is shown to naturally explain a number of otherwise puzzling observed features, such as the radio arc and bridge, possibly the ionized minispiral and some aspects of the general energy balance of this region.

1. EXISTENCE OF A STRONG MAGNETIC FIELD

There is accumulating evidence that the galactic center harbours a strong magnetic field. This comes from Faraday rotation measurements (Tsuboi et al., 1986, Sofue et al., 1987) both in the arc and bridge, which imply at least a 100μG field in these features (Heyvaerts et al., 1988). Indirect evidence concerning the rigidity of arc filaments (Yusef Zadeh and Morris, 1987) points to larger values. Infrared spectropolarimetry at $8-10\mu$ (Aitken et al., 1986) shows the field to be organized along the northern arm, and to be as high as 10^{-2} gauss. Similar organization is observed by Werner et al. (1988) in the 3pc dust ring at 100μ, with a value consistent with 10^{-2} gauss. More direct measurements of the field in these regions would obviously be of the utmost interest.

2. EVOLUTION OF THE MAGNETIC FIELD

This field, and associated currents, influence fluid motion by the $\vec{J} \times \vec{B}$ force. Conversely the field evolution is controlled by the motions and by dissipative processes through Faraday and Ohm's law which combine in equation :

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$$\frac{\partial \vec{B}}{\partial t} = \mathrm{rot}\ (\vec{v} \times \vec{B}) + \eta \Delta \vec{B} \qquad (1)$$

where $\eta = (\mu_0 \sigma)^{-1}$ is the field diffusivity and σ the electric conductivity. Let ℓ be a characteristic field gradient scale. The ratio of the first (convective) term to the second (resistive) one on the r.h.s. of (1) is the magnetic Reynolds number $R \simeq (\ell v/\eta)$. For ionized material, v = 100 km/s, $\ell \simeq$ 1pc, R is 10^{18}! The diffusive term is usually negligible, and the flux-freezing theorem, which states that in this limit field and matter move together, is applicable. Nevertheless, the zero field diffusivity limit may become inapplicable at special places in the flow, where ℓ happens to be much shorter. This is the case of reconnection flows, in which two different field systems are pressed together. A resistive boundary layer develops at their interface, which has the shape of a thin line in which resistivity controls the flow. Reconnection takes place there, between field lines of the two systems, which are then quickly pulled away from the reconnection region by a strong tension force. So-called tearing-mode instabilities spontaneously develop flows in which reconnection takes place. If they develop into a turbulent regime, the singular boundary-layer line may become an essentially fractal object. Reconnection then seems to occur everywhere in the turbulent region, releasing substantial magnetic energy into turbulent kinetic energy which quickly thermalizes. This will be refered to as diffuse, or turbulent, reconnection.

Microscopic plasma instabilities, which may be triggered when current densities pass certain thresholds, have the potential of enormously increasing the magnetic diffusivity in regions where they develop. Thresholds, however, are high, of order $j_* \simeq 10\ ne\ V_{Ti}$ for the ion-cyclotron instability, where V_{Ti} is the ion thermal velocity. For a typical ionized environment, this is 4 10^{-6} A m^{-2}, a current density which corresponds to a field change of a milligauss in 20 km. We expect this situation when scale-reducing MHD processes have been acting. G. Benford presents in this meeting a model based on the idea that some large scale circuit is filamented in currents of that size, the global circuit so becoming resistive rather than inductive. The reason for this extreme filamentation is certainly a crucial issue for his model.

Only reconnecting or, more generally, resistive regions can support field aligned electric fields, and are then a privileged site for D.C. electric acceleration. Otherwise the law $\vec{E} + \vec{v} \times \vec{B} = 0$ holds, and $\vec{E}$ only causes drift of charged particles at velocity $(\vec{E} \times \vec{B})/B^2$, not acceleration to high energy.

3. ENERGY DENSITIES

Table I allows us to compare the importance of various forces developed in the 50pcs from galactic center, which is a relatively high energy density region.

The kinetic (and gravitational) energy of dense molecular matter dominates other energies, including magnetic, but not always by a large margin. By contrast the field controls the motion of other more tenuous material. It may however be confined by the pressure of a possible X-ray emitting gas, at 10^8K and density 1cm^{-3}. This situation, where a dense fluid imposes its motions to a field which itself dominates a tenuous medium is

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familiar from other fields of astro– and geophysics such as, for example, the system of the dense photosphere/tenuous corona on the sun.

Region	Parameters	Ergs cm^{-3}	Reference
Molecular ring	$n = 10^5\ cm^{-3}$; $v = 100 km/s$ $T = 350K$	$nkT = 5\ 10^{-9}$ $1/2\rho v^2 = 1.6 10^{-5}$.	Güsten (1987)
Field in molecular ring	10^{-2} Gauss	$B^2/2\mu_0 = 4 10^{-6}$	Aitken et al. (1986)
Ionized matter (bridge)	$n = 300 cm^{-3}$; $v \simeq 40 km/s$ $T = 7800K$	$nkT = 3 10^{-10}$ $1/2\rho v^2 = 8 10^{-9}$	Pauls and Mezger (1980)
Field in arc and bridge	10^{-3} Gauss	$B^2/2\mu_0 = 4 10^{-8}$	Yusef Zadeh and Morris (1987) Sofue et al.(1987)
Molecular clouds (not 2pc ring)	$n = 10^4\ cm^{-3}$; $v \simeq 40 km/s$ $T = 70K$	$nkT = 10^{-10}$ $1/2\rho v^2 = 2 10^{-7}$.	Genzel and Townes (1987)
X–ray gas	$n = 1 cm^{-3}$; $T = 10^8 K$	$nkT = 1.4 10^{-8}$	Watson et al. (1981)

Table I. A comparison of representative energy densities for various components of the galactic center region.

The consequences of this are observed to be :
(1) magnetic heating of the tenuous medium.
(2) dynamic MHD activity (erupting prominences, flares..).

It is then natural to expect some similiarity in behaviour (and morphology) between the solar corona/heliosphere and the galactic center region. This is explored by Heyvaerts et al. (1988) (hereafter HNP (1988) for brevity).

The physics of this driver/field/coronal medium coupling is described below and depends on whether the field is open or closes back on the differentially rotating driver.

4. COUPLING OF OPEN FIELDS TO A ROTATING DRIVER

At the large scale, the dense fluid may be regarded as condensed in a plane and in circular motion. If the overlying magnetic structure is open and axisymmetric a stationary state is possible, which may support a thermal or centrifugally driven wind (Blandford and Payne, 1982). Shibata and Uchida (1987) and Uchida et al. (1985) explored numerically the ill–known non–stationary evolution, starting with a non–equilibrium situation in the dense

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driving disk. They observe the formation of a transient jet with a shell structure, which is somewhat reminiscent of the "GCL radio lobe" and has some features of the observed rotation measure map (Tsuboi et al., 1986). For further discussion, see Shibata (this meeting). This relaxing twist concept, however, needs arbitrary initial conditions.
Realistically, initial non-equilibrium, caused for example by cloud collision, should be non-axisymmetric, and 3-dimensional effects, like field line tangling, are likely to occur, but more difficult to model.

5. COUPLING OF CLOSED FIELDS TO DIFFERENTIALLY ROTATING DRIVER

When field lines close back on their dense driver, the physics of the matter/field coupling is different. In perfect MHD ($\eta = o$) the evolution is dominated by the fact that the two footpoints of a same field line on the "driver" must remain magnetically connected during the evolution. When there is differential rotation, no stationary state can be reached. This connectivity condition is usually not compatible with $\vec{B}$ remaining curl-free in the coronal medium. This means that electric currents are driven into the tenuous medium. What is then the fate of this evolving magnetic structure and its stability properties ?

This situation can be met in a number of different geometries. For example Yusef Zadeh and Morris (1987) propose that the radio arc structure be a large scale (coronal-type) force free field driven by material faraway in the halo or in the disk of the galaxy. This looks like a simple and consistent idea. Probably the confinement of the current carrying structure may be achieved by the X-ray gas. Note that this pictures the phenomenon as unrelated to galactic nuclear activity. If so, we should expect to discover similar arc structures wherever the large scale galactic field happens to become concentrated (in large molecular clouds ?).

Another plausible situation is when the field is attached to a differentially rotating disk. If the field scale is somewhat smaller than the radius of the disk, this can also be conveniently idealized as a magnetic configuration having translational (instead of azimuthal) symmetry in one "horizontal" coordinate z, acted on by boundary motions $\vec{v}$ (x, y = o) = v(x) $\hat{e}_z$, where x is the other horizontal coordinate and the boundary is the plane y = o. The field structure pervades the half space y > o. This is an archetypal problem in solar physics, where it models the coronal evolution in the presence of shear flow on the boundary. The sequence of magnetohydrostatic equilibria produced by a given (slow) boundary motion has been studied numerically and analytically. It is the solution, at each time, of a complicated non-linear elliptic partial differential equation (Low, 1977 ; Heyvaerts et al., 1982 ; Birn and Schindler, 1981).

The results are conveniently described as a function of the total current, I, driven into the corona (though I is not necessarily a monotonic function of shear). It is found that the sequence of equilibria corresponding to an increase of the current, starting from the potential solution (I = o), terminates at some finite value of the total current, I^*. For $I < I^*$ there usually exists a number of other equilibria with magnetic island-topology (field lines that never reach the boundary). For $I > I^*$, there usually still exists an equilibrium with open field line topology, but no "closed" equilibrium (Heyvaerts et al., 1982). A transition from the last closed configuration at $I = I^*$ to the remaining open one can only take place through a dynamic event where $\vec{J} \times \vec{B}$ forces are temporarily

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unbalanced. It is conceivable that such a dynamic impulsive event be the cause of erupting prominences and coronal mass ejection events observed on the sun (Wagner, 1984) which are known to be driven by Lorentz forces. The dynamic regime, itself, is not as well modelled as the quasistatic evolution which probably triggers it.

Resistive stability is also important. For example the open equilibria refered to above are unstable to reconnection (Kopp and Pneuman, 1976 ; Malherbe et al., 1984). This is the cause of those large solar flares which occur immediately after a coronal mass ejection.

On the other hand, even closed structures may be subject to resistive tearing-mode instabilities on some time scale longer than the Alfvén transit time scale. If the boundary motion is slow enough, the system will not reach the loss of equilibrium point, but will evolve through a resistive sequence, where turbulent diffuse reconnection permanently releases part of the magnetic energy injected in the structure by the motions of the driver. The heating and magnetic reconfiguration of a structure, due to the decay of turbulence associated with diffuse reconnection is amenable to quantitative consideration thanks to a theory elaborated by fusion physicists (see the review article by Taylor, 1986). Generalisations have been used to calculate the final state of solar flares (Norman and Heyvaerts, 1983) and coronal heating (Heyvaerts and Priest, 1984). It is interesting to note that the ideas put forward by Yusef Zadeh and Morris (1987) for the energization of the radio arc may actually be described as such an "internal diffuse reconnection process", and are entirely consistent with this known physics.

Recently, Heyvaerts and Priest (1988), have modelled a thin disk driving a closed corona above it, which is maintained in stationary state by the diffuse reconnection process. The heating of the outer medium and the back reaction of Lorentz forces on the disk dynamics have been calculated. The nature of their solutions depends on a couple of dimensionless parameters, the most important one being the ratio of magnetic to gravitational energy of the disk/corona system :

$$\lambda = \frac{4\pi R^3 B_o^{\,2}}{\mu_o} \Big/ \left[\frac{GMM_D}{R}\right] \qquad (2)$$

where R is the disk radius, B_o its surface field and M_D its mass, while M is the mass which creates the gravitation. For stability λ should be less than some number of order unity. For the sun, $\lambda = 10^{-16}$. However for the molecular torus, with $B_o \simeq 3$ milligauss, we get $\lambda \simeq 0.25$. This is a rather exotic degree of magnetization indeed ! The rate of coronal heating associated to it should approach the maximum conceivable (see also HNP (1988)) which is :

$$H_{cor} = \frac{4\pi R^3 B_o^{\,2}}{\mu_o} \sqrt{\frac{GM}{R^3}} \simeq 3\ 10^{39} \text{ ergs s}^{-1} \ . \qquad (3)$$

This is indeed enough to account for the total diffuse X-ray luminosity of the 50pc region ($8\ 10^{36}$ ergs s^{-1} according to Skinner et al. (1987)), but perhaps marginal to feed the total losses of the strong wind that we should expect.

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Indeed, if a gas at 10^8K is present, its thermal velocity so much exceeds the escape velocity out of the galactic potential well that a strong wind must exist, unless this gas is entirely confined by a completely closed field, which is quite unlikely. Standard thermal wind theory gives, assuming a density of 1 cm^{-3} at 2pc for this very hot gas, a mass loss rate

$$\dot{M} = 1.5\ 10^{-3}\ M_{\odot}\ yr^{-1} \tag{4}$$

and an associated enthalpy loss rate of 2 10^{39} ergs s^{-1}, to which similar kinetic energy losses add. This led HNP (1988) to consider the possibility that the galactic center also harbours some compact magnetically active object at subparsec scale, presumably a disk around some compact and massive central object. Scaling of the above rate of coronal heating to a more compact object, with $B_0 \simeq R^{-3}$, easily reaches values larger than 10^{40} ergs s^{-1}. Later on we envisage the two possible models : the "1-Disk" model (the molecular ring is the only accretion disk structure in the G.C.) and the "2-Disk" model (there also exists another, more compact, magnetically active object (a disk too presumably)). Note that the self gravitating mass that is able to bind a flux corresponding to a milligauss field pervading a fraction f_B of the 2pc sphere is, demanding gravitational energy to exceed magnetic energy :

$$M_{Bind} = f_B\ B(\text{milligauss})\ .\ 8\ 10^5\ M_{\odot} \tag{5}$$

6. EJECTION OF MAGNETIC STRUCTURES

As explained in paragraph 5, the quasistatic evolution of the magnetic structure overlying a sheared driver is likely to lead to a dynamic expansion of part of these structures when the stress exceeds some threshold. This dynamic motion is driven by unbalanced $\vec{J} \times \vec{B}$ forces. As a first approach to modeling this complex MHD flow, HNP (1988) generalized to the galactic center gravitational environment an early theory developed by Anzer (1978) to describe coronal mass ejections on the sun. In this theory the force which causes the structure (modeled as a current carrying loop) to expand is the imbalance between the magnetic pressure of the field (induced by this very current) at the inner and outer edges of the gas-containing loop. In reality the magnetic structure, and the current and mass distribution will be much more complex. This approach has the advantage of simplicity and should be sufficient to test semi-quantitatively the order of magnitude of the ejection velocities that can be reached and to identify the parameters which control the main features of the motion. The galactic gravitational field model adopted includes a point mass, an isothermal cluster and a flat disk of uniform density. With $x = r/R_*$, $R_* = 2$pc, M_* being a reference mass and λ_G, $\lambda_{C\ell}$, λ_C three coefficients which add to 1, HNP (1988) model the gravitational field as :

$$g(x) = \frac{GM_*}{R_*^2}\left(\lambda_G + \lambda_{C\ell}/x + \lambda_C/x^2\right) . \tag{6}$$

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They include a drag force due to interaction with ambient gas (parameter γ_D), and allow for a self similar increase of the loop cross section. The equation of motion for the apex of the loop is, in some normalized time (HNP (1988)) :

$$\frac{d^2x}{dt^2} = \frac{\gamma_M - \lambda_c}{x^2} - \frac{\lambda_{c\ell}}{x} - \lambda_G - \gamma_D \, x \left(\frac{dx}{dt}\right)^2 . \qquad (7)$$

The γ_M parameter is the ratio of magnetic to gravitational energy of the loop. It differs from the λ parameter defined in eq.(2). It must exceed λ_c ($\simeq 0.4$) for loop inflation to take place, and should not be much larger than a few, otherwise loop inflation should have occurred earlier during the evolution of the loop. It is found by HNP (1988) that inflation velocities of some 10^2 km/s are possible at 30pc, and that only those loops which have γ_M equal to unity or so (γ_M = 2 or 3) can reach 50pc starting inflation at 2pc. Loops with slightly smaller γ_M ($\gamma_M \simeq 0.7$ or 0.8) can only do so if emitted from subparsec scales. Loops with still smaller γ_M stop expanding at distances of order 3pc/12pc. It takes a field larger than 200μG for a loop of density 10^2 cm^{-3} to expand "rigidly", not being distorted by the differential azimuthal rotation that specific angular momentum conservation of matter alone (ignoring magnetic torques) would imply. When they are accelerated off their driver, loops must be on the verge of kink instability, since the condition for loss of equilibrium is almost the same as for the kink instability. Therefore loops may buckle, and detach off their driver by reconnecting on themselves. Thereafter they expand around their center of mass which is, but for a small drag, in free motion. The azimuthal motion results from total angular momentum conservation, except for the drag, which remains small if the environment is tenuous. Stability of the detached loop depends on expansion, current and density profiles. This issue can only be meaningfully addressed in a more realistic model. Field aligned dynamics is another important aspect that has been left out of these calculations.

7. CLOUD/FIELD COLLISIONS

The galactic center region is most probably filled with magnetic fields of varying intensity, and by gas of different densities. If magnetic inhomogeneities are large enough, the concept of "magnetic features" will make sense (just as the concept of a cloud does). What happens when clouds and magnetic features, or when different such features collide ? The issue depends on the relative size of the colliding objects.

Consider first an extended field and a smaller cloud, unmagnetized, say. A safe physical picture of what happens can be drawn from the analog with the motion of the satellite Io in Jupiter's magnetosphere (Herbert, 1985). This motion drives by the ($\vec{v} \times \vec{B}$) electromotive force a surface current at the interface between field and body. This current causes a perturbation of the field line with which it is temporarily in contact. Once the body has passed, this pertubation propagates away along the field line at the Alfvén speed. All these together create an "Alfvenic wake", along which electric current flows, closing at infinity the surface current flowing on the body.

A similar circuit should set up in the case considered by G. Benford (this meeting) of the collision of a large cloud with an extended magnetic field.

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Benford takes the view that the current path materializes as radio arc and bridge, thus associating these features with the edges of any cloud not sharing the field motion. The reason why his circuit should indeed close through the radio arc is not yet clear, however.

The moving body is decelerated with respect to the rest frame of the sources of the magnetic field. It works against a pressure $B^2/2\mu_o$ on its surface exposed to the field. If its size is a, in the direction of motion, the equation of motion relative to the field is :

$$\rho a \frac{dv}{dt} = - \frac{B^2}{2\mu_o} \tag{8}$$

where ρ is the cloud density. The characteristic braking time is then

$$\tau_B = \left[\frac{a}{v}\right] \left[\frac{v^2}{v_A^2}\right] \tag{9}$$

where v_A is the Alfvén velocity calculated with the cloud density. Typically, for 10^{-3} G and cloud density 10^4 cm^{-3}, v_A = 20 km/s and τ_B is a small number of times the cloud self crossing time a/v. This is a very effective drag and may be a very effective help to accretion. The picture, however, should be modified if the strong field comes in rather individualized features, of cross size smaller than the cloud. Then, the collision of the magnetic loop with the cloud generates an MHD shock system. A sonic shock wave forms in the cloud, ahead of the flux tube, while a fast MHD shock compresses, in a short time, the flux tube. The deformation of this tube caused by this interaction propagates in the tube length direction as an Alfvén signal. If this Alfvén time scale is short, the loop is only weakly deformed. The cloud gas just in front of the loop is shocked and essentially brought to rest with respect to it. The braking time for the relative motion is the time it needs for the loop to sweep up an amount of gas equal to its own mass. For tenous enough clouds this causes a braking, which has been included in our calculations (HNP, 1988). For a very massive cloud, the result of such a collision is that the loop is caught by the cloud and brought to its own motion. Here again, the gas that has been disturbed from its gravitational motion is susceptible to accretion.

8. COLLISIONS BETWEEN FIELD SYSTEMS

If the magnetic field is inhomogeneous enough for the concept of separate magnetic features to make sense, one may wonder about the effects of their collisions.

According to Sofue (1984) a starburst may have shocked the interstellar gas in the galactic center region and cleared a region bounded by the "galactic center lobe" from its dense gas and magnetic field forming a cavity filled with hot gas and bounded by a magnetized boundary. A strong hot wind, as implied by a hot X-ray emitting gas, could have carved a similar cavity by the injection of several 10^{39} ergs s^{-1} during 10^7 yrs (HNP (1988)). This boundary may be one of the features involved in collisions among field systems.

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Sofue and Fujimoto (1987) suggest that a magnetized one-sided jet emanating from the nucleus collides with this boundary, accelerating particles at the collision, thus illuminating by synchroton radiation those field lines which are involved in the interaction. Though Fujimoto and Sofue (1986) analyze some of the forces that may influence the structure and motion of such a jet, they do not propose any specific explanation for the formation of this one-sided jet.

Heyvaerts, Norman and Pudritz (HNP (1988)) suggest that a magnetic loop, which has detached from its driver, and is expanding for the reasons mentioned above, is presently colliding with, and even perforating, the GCL lobe boundary. Sofue and Fujimoto's view is an open-flux tube version of Heyvaerts et al.'s one, and shares common physics with it. The latter theory is, we believe, more able to explain a number of observed facts (see below), especially so since radio filaments, fainter but analogous to the bridge ones, have been seen on the other side of the galactic plane. Note that in both these theories, the "GCL" radio ridges are actually "lit" vertical plumes on this boundary, not its edges. Another, weaker or older, interaction of the same type should cause the western ridge and Sgr C radio emitting region.

The collision of two field systems gives rise to two main effects. An electromotive electric field $\vec{v} \times (\vec{B}_2 - \vec{B}_1)$, where $\vec{v}$ is the relative velocity, is developed at the interface and drives a current system, just as in the case of cloud/field collision. In this respect HNP's and Sofue and Fujimoto's ideas share common content with Benford's, the difference being in the nature of the bodies creating the electromotive effect, and in the definition of the current circuits. Second, collision between field systems is the archetypal situation where reconnection occurs.

9. LOOP/GCL COLLISION

In the view of HNP (1988), expanding loops will collide with the GCL magnetic boundary (which they assume to exist). If this boundary comes in discrete flux tubes, as Yusef Zadeh and Morris (1987) envisage, this does not make much difference. Because the material on the boundary is in galactic rotation, while the loop is not, GCL material will ram in the azimuthal direction in the loop. Because the loop is expanding and because its kinetic energy is larger than the magnetic one in the GCL boundary, it will also penetrate the boundary and intrude on the other side. As a result a complicated flow pattern will develop. If the loop were only to graze on the boundary, a surface wave system would form. However, because the loop penetrates, these surface waves are strongly non-linearized. Actually the loop "hooks" those boundary field lines which are brought by galactic rotation into contact with it. The magnetic tension stretches these field lines between the contact regions with the loop, while the signal that part of this boundary field line has been brought to rest with respect to the loop propagates along it at the Alfvén speed. This causes this field to align, above and below the contacts with the loop, along an "alfvenic wake" (see Fig. 1). Reconnection may free the hooked field lines. The flow itself may also bring boundary field lines round the protruding loop. Those field lines (more correctly small flux tubes) which have just been reconnected become lit by the particles accelerated in the process, and are pulled violently by magnetic tension away from the contact region (Fig. 1) (heating due to the relative motion of these flux

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strands with respect to the ambient medium is also expected (HNP (1988)).

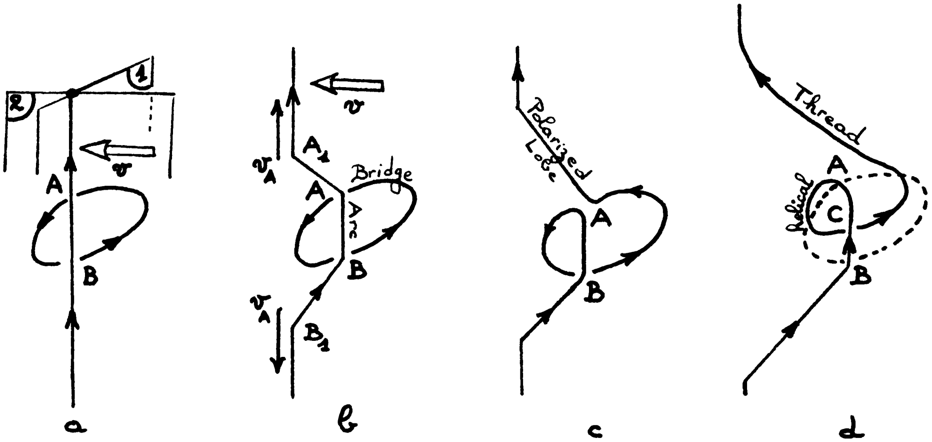

Figure 1. Time sequence history of the interaction of two elementary flux tubes, one in the loop (in plane (1) in Fig. a) and the other in GCL boundary (plane (2) in Fig. a). The latter is carried along by galactic rotation (thick arrow). (a) First contact at A and B. (b) The segment AB is "hooked". Magnetic tension stretches field between A and B. An alfvenic signal has propagated up to A_1 and B_1 the information that motion has stopped. The field connects AA_1 and BB_1 along "alfvenic wakes". (c) Reconnection occurs at A (d). The magnetic tension pulls the field line away from A, and moves the contact point from B to C, where reconnection will occur later on.

This picture has the potential of explaining :

- the linearity of arcs (stretched/compressed features).
- the rotation measure inversion observed by Tsuboi et al. (1986), in compatibility with the straightness of arcs.
- the injection of particles of high energy (GeV's) along reconnected features.
- the existence, emission and size of non thermal lobes.
- the interaction between arc and bridge going on at points A and B (Yusef Zadeh and Morris, 1988).
- the threads and helical filaments as recently reconnected structures as pictured in Fig. 1d.
- the fact that field interaction is going on at polarized spot on the arc, as at point C on our Fig. 1d (Inoue, this meeting). More quantitative details are in HNP (1988).

10. LOOP/TORUS COLLISION

The molecular torus is also a place where the field is ordered (Werner et al., 1988). Two scenarios are conceivable according to whether one or two accretion disks are considered (see section 5). If there is a compact magnetically active central object shedding loops, these will collide with the torus from inside. However the magnetic rigidity of the torus is large, and loop

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penetration deep inside the torus should not occur. For a 10 mG field the gravitational rotation in the torus is superalfvenic. This means that all the magnetic perturbations which occur at the torus/loop interaction points are carried downwind in the sense of galactic rotation, on the outer "skin" of the torus. If the eastern arm and the bar are regarded as a piece of the most recently collided loop, the minispiral morphology of the ionized gas at the torus inner boundary may be naturally explained by the decay into heat of perturbations induced at the interaction points (that is at intersection of bar with northern arm and western arc ; HNP (1988)). These places should show some nonthermal features too.

This kind of interaction is based on the same physics as the loop/GCL collision. It has the potential of explaining several puzzling aspects of the physics of the torus (HNP, 1988) :

– the recurrent loop shedding from the central object feeds energy in the form of turbulent alfvenic fluctuations in the torus, and heats it by their decay. A rate of heating of 3 10^{37} ergs s^{-1} is a reasonable expectation.

– this interaction maintains turbulent velocities in the torus, and has the potential of confining its inner boundary (Güsten, 1987).

– if indeed our explanation of the "minispiral" morphology is consistent, this implies v_A(torus) < v(galactic) < v_A(bar), that is, it "predicts" a field of order 10 mG in the torus.

– the organization of $\vec{B}$ in the plane of the torus results from its stretching by differential rotation, and its very strength may be regarded as resulting from the saturation of this ω-effect by Lorentz forces.

– some kinematical peculiarities of ionized gas at the northern and western arm/bar intersection could be attributed to reconnection flows. Some more quantitative details are in HNP (1988).

If the loop emitter is the torus itself, detached expanding loops may still collide back with it. Most of the above phenomena are still expected, but for the role of energy injection in the torus. The loop inflation appears as a process by which rotational energy is transformed into magnetic and gravitational energy, and the collision between loop and torus merely redistributes it as turbulent energy. The dissipation of this energy ultimately causes the shrinking of the molecular torus. This is a help to accretion, just as cloud/cloud collisions are in an hypothetical non-magnetized regime.

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