A MAGNETIC LOOP MODEL FOR STRUCTURE AND ACTIVITY IN THE GALACTIC CENTER

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ABSTRACT

We present a comprehensive model to explain the remarkable filamentary and arclike structure in the Galactic center in terms of strongly magnetized structures emerging from a central object of mass of order $10^6 M_\odot$. We show how such structures would propagate out into the lobe and interact with the inner molecular torus at $\sim$2 pc and with the Galactic center lobe at $\sim$50 pc via shocks and reconnection. This active central region is envisaged as behaving as a bound, highly magnetized, corona. It is shown that many aspects of the observed radio morphology and energy balance of the galactic center region corona can be understood including the structure and kinematics of the Galactic center lobe boundary, the radio arch filaments and bridges, the polarization, the X-ray emission, the characteristic structure of the inner three-pronged structure, and some of its kinematical peculiarities.

The energy balance of the 2 pc molecular torus can be explained as arising from quasi-continuous energy deposition via the interaction with outwardly propagating loops. The substantial line widths observed in the torus can be manifestations of Alfvén wave turbulence caused by this interaction. Our analysis implies that Sgr A actually should be the closed magnetic corona of the molecular 2 pc torus. The observation of a high-temperature X-ray emitting gas implies that a wind is blown from the center region. The latter can be powered by magnetic coronal heating processes in the vicinity of the central object. The entire Galactic center region is expected to be filled with filamentary structures. The model implies that the object in which this activity originates must be compact and strongly magnetized.

Subject headings: galaxies: The Galaxy — galaxies: nuclei — hydromagnetics

1. INTRODUCTION

The Galactic center harbors remarkably filamentary and ordered structures on scales within $\sim 10^2$ pc of the nucleus. On this largest scale, radio emission extends perpendicular to the Galactic plane demarcating a bubble-like structure. This Galactic center lobe (GCL) may indeed be modeled as a radio emitting shell with "walls" of order 16 pc thick (Sofue 1985). A 20 pc section of it near the Galactic plane, known as the "radio arc," has been resolved into a remarkable series of parallel, nearly straight filaments (Yusef-Zadeh, Morris, and Chance 1984; Morris and Yusef-Zadeh 1985). Cutting nearly perpendicular to these structures, the radio "bridge," observed in older radio surveys (e.g. Altenhoff et al. 1978) is also resolved into filaments. This trend is seen again at 1 pc scales which contains the famous spiral-like distribution of radio emitting gas (Ekers et al. 1983; Lo and Claussen 1983). These structures also appear to be "braided." The detailed properties of this entire region have been exhaustively reviewed (Brown and Lüst 1984; Backer 1987; Genzel and Townes 1987).

We propose that radio structures from subparsec to 100 pc scales are manifestations of magnetic activity in a central source object (see Heyvaerts, Pudritz, and Norman 1987). The observed features cannot simply be limb-brightened structures but are apparently truly one dimensional, and we suggest that they are evidence for magnetic loops. These are produced on subparsec scales, and expand out to 30-100 pc regions. A strongly magnetized body which is highly sheared (e.g., an accretion disk) generates loops of magnetic flux which erupt from their source and expand into the surrounding gas. Using a simple model of loop generation and propagation, we show that these structures can expand out to 30 pc. The interaction of these expanding loops with the 2 pc molecular torus and the GCL produces shocks which heats gas and accelerates particles. We demonstrate that many detailed properties of disturbed and ionized gas in the Galactic center can be explained in this way.

The nature of the magnetic activity which produces these loops puts very interesting constraints on a central body. We show from radio rotation measure observations that the magnetic flux associated with these filamentary structures could not have been produced in a stellar environment, because these are too flux poor by orders of magnitude. The minimum mass body which can trap the huge magnetic flux ascribed to the observed filamentary structures is of order $10^5 M_\odot$. The plausible sources of activity are associated with IRS 16, the pair IRS 16-Sgr A*, or perhaps a strongly magnetized accretion disk around a central black hole. This central activity drives a magnetically dominated evolution of the GCL, which gives its peculiar irregular, filamentary structure.

A major prediction of our model is that the ionized radio emitting gas which is trapped inside magnetic filaments, is expanding away from a source on sub-0.1 pc scales out to 30–50 pc. We show that expansion of loops at 300–400 km s$^{-1}$ is possible at subparsec scales. There is no need to suppose therefore that those peculiar velocities are gravitational in origin. In particular, a $10^6 M_\odot$ black hole is not required in our model (e.g. Genzel and Townes 1987). The remarkable radio morphology of the Galactic center including the entire Sgr A radio source itself can all be unified in the context of our model of expanding magnetized loops interacting with the interstellar medium.

The physics of loop eruption and subsequent propagation in an external medium has a well-studied analog, namely, the
eruption of coronal transients on the Sun (Wagner 1984). It is known that large twisted magnetic loops erupt off the Sun about once per month, and signatures of their propagation are observed up to a distance of at least $10^4 R_\odot$ (Wagner 1984). Observational constraints on our model suggest that the central body in the Galactic center should have comparable magnetic and gravitational energy densities so that in principle, a highly disturbed, transient, yet structured medium could be produced out to a considerable distance from the source. Section II presents the observations which our model should explain. In § III, the basic assumptions are given, while § IV sets up and solves the simple magnetic loop equations. Constraints on the nature of the central object are discussed in § V, applications to the 2 pc scales in § VI, the structure of Sgr A in § VII, and the physics of the radio arc, bridge, and "threads" in § VII.

II. OBSERVATIONS

We discuss the structures in the Galactic center starting at the 100 pc scale, gradually focusing down to subparsec regions, stressing the possible role of magnetized plasma phenomena.

a) The GCL (100 pc)

i) A Stubby Radio Structure in the Galactic Center

This structure was found in the low-frequency Bonn surveys (Altenhoff et al. 1978; Downes et al. 1978). Recent higher resolution maps of this region (Sofue and Handa 1984) show a continuous "Ω-shaped" radio structure, called the Galactic center lobe (GCL). Sofue (1985) has modeled the brightness distribution as arising from thermal emission in a cylindrical shell of total mass $4 \times 10^4 M_\odot$.

ii) Lobes of Highly Polarized Emission

These lobes are part of the GCL to the north and south of the radio arc (Seiradakis et al. 1985; Tsuboi et al. 1986). They reach heights of 100 pc above and below the Galactic plane. The polarization at 10.8 GHz achieves values of 40% and indicates the presence of a strong, ordered transverse and slightly wavy magnetic field (Tsuboi et al. 1986). The length of field irregularities is 10–30 pc. The most intense polarized emission arises from a point just to the north of where the bridge filaments cross the radio arc on the GCL.

Constraints on the line of sight field strengths may be deduced from the rotation measures, typically $\sim 1000$ rad m$^{-2}$; $B$ being the line-of-sight component of the magnetic field, the rotation measure is given by

$$RM = 0.8 \int n_e B dl \text{ rad m}^{-2}$$

where $n_e$ is the electron density in cm$^{-3}$, $l$ is in parsecs, and $B$ in microgauss. With our later estimate, $l \approx$ a few parsecs, and $n_e = 5 \text{ cm}^{-3}$. This lead us to think that $B \approx 0.1–1$ mG. The RM changes sign between the north and south polarized parts of the GCL such that the line-of-sight field is toward the observer in the north (RM positive) and pointed away from the observer in the south (RM negative) (Tsuboi et al. 1986). Recently, Sofue and Fujimoto (1986) proposed that such a morphology would arise if a jet (the bridge filaments) interacts with a poloidal field in the rotating GCL. Magnetic loops would also provide distortions of a poloidal GCL field, which can account in detail for the RM results (see § VII).

iii) Radio Arc and Bridge Filaments (30 pc)

These two structures have been described in detail in a series of papers and are well known. We refer the reader, for example, to Yusef-Zadeh, Morris, and Chance (1984). Recently other bridge filaments have been found in the south (Yusef-Zadeh, Morris, and Van Gorkom 1987). Bridge filaments appear to be associated with molecular gas of similar velocity (Serabyn and Güsten 1987a, b). Recombination line studies along the arc and northern bridge show, however, strong differences in their gas properties (Pauls et al. 1976; Pauls and Mezger 1980). The predominantly negative radial velocities indicate gas motion toward the observer. This is important because galactic rotation is away from the observer at the western galactic longitudes. The velocities published in Pauls et al. (1976) indicate a trend of increasingly negative velocity as one moves along the bridge toward Sgr A ($-14$ to $-48$ km s$^{-1}$). The typical LTE temperature derived from these studies is 7000 K, and typical densities are $n_e \approx 10^2$ cm$^{-3}$ (Pauls and Metzger 1980). The thermal gas along the bridge then has a pressure of order:

$$(nT)_{\text{recomb}} = 7 \times 10^8 \left(\frac{n}{100 \text{ cm}^{-3}}\right) \left(\frac{T}{7000 \text{ K}}\right) \text{ cm}^{-3} \text{ K}.$$  

iv) Threads (30 pc)

These are several apparently one-dimensional structures with lengths $\geq 30$ pc and width $\leq 0.5$ pc which have uniform brightness along their lengths (Morris and Yusef-Zadeh 1985). These structures appear amidst the filaments comprising the radio bridge. The authors rule out limb-brightened two-dimensional structures such as shock fronts, jets, and wakes and suggest one-dimensional magnetic threads as an important possibility.

v) X-Ray Emission

The GCL may be filled with hot, X-ray emitting gas. Watson et al. (1981) observed a $1\times 1$ field centered on the Galactic nucleus with the Einstein IPC and detected a diffuse component to the overall X-ray emission, with a total luminosity $L_x = 2.2 \times 10^{36}$ ergs s$^{-1}$ (1–4 keV band). The volume of X-ray emitting gas is $V_x \approx 1.5 \times 10^5$ pc$^3$. If this emission is due to a hot plasma its temperature should be $10^{7}–10^{8}$ K, and the mean electron density $n_e \approx 1$ cm$^{-3}$. Watson et al. (1981) argue that a very high X-ray temperature of $10^8$ K is quite possible.

The presence of X-ray emitting gas implies a pressure associated with it, of order

$$(nT)_x \approx 10^3 n_e (T_x/10^8 \text{ K}) \text{ cm}^{-3} \text{ K}.$$  

This is much higher than the inferred pressure of the recombining gas (eq. [2.2]). The only way that the bridge filament could be in pressure equilibrium with the high-pressure X-ray emitting medium, is that the bridge be strongly magnetized. Actually this requires from equations (2.2) and (2.3)

$$\beta_{\text{bridge}} = \frac{P_{\text{recomb}}}{B^2/8\pi n_{\text{bridge}}} \leq \frac{(nT)_{\text{recomb}}}{(nT)_x} = 0.007,$$

where $B_{\text{bridge}}$ is the bridge magnetic field and $P_{\text{recomb}}$ is the thermal pressure of gas enclosed in the loop. Even conservative estimates require $\beta_{\text{bridge}} \leq 0.1$, so the bridge must be a magnetically dominated structure if it is to keep in pressure equilibrium and remain thermally insulated from the X-ray emitting gas. Bridge filaments then must be magnetic loops, confined by the pressure of the very hot X-ray emitting gas.
which may fill the GCL. The required field strength is $B \geq 0.6 \times 10^{-3} (T_d/10^8 \text{ K})^{1/2} \text{ G}$.

vi) Associated Molecular Clouds

Brown and Liszt (1984) emphasize the relationship between the 40–60 km s\(^{-1}\) molecular clouds over the Sgr A complex, and the appearance of the radio arc.\(^{12}\)CO observations show a fairly abrupt (positive longitude) boundary along which the radio arc appears to run. We tentatively identify these clouds as forming an annular distribution which is just beyond the GCL shock.

b) Sgr A (10 pc)

Yusef-Zadeh and Morris (1986) have recently reviewed the high-resolution VLA observations of the Sgr A complex. Prominent features include an elliptical, shell-like structure in Sgr A East, and large-scale, curved protrusions which are associated with Sgr A West. These likely emit by bremsstrahlung. Of importance to our unifying picture is the fact that some of the protrusions are linked to the “bar” as well as to both northern and southern arms of the 1 pc scale ring of ionized gas at the heart of Sgr A West. Ho et al. (1985) have studied a wisp structure associated with Sgr A, which is polarized to the 10%-20% level. The magnetic field is interpreted to be aligned parallel to the filament, and these authors deduce an equipartition field strength of order 0.3 mG.

c) Radio Ring and Molecular Torus (1–5 pc)

i) Radio Ring

This structure, studied by Ekers et al. (1983) and Lo and Claussen (1983), has three features: the western arc, the northern arm, and an east-west “bar” which intersects the former two structures. While early observations found a spiral-like structure for the radio emission, recent low-intensity observations show a nearly complete “ring” of emission. Detailed [Ne ii] observations by Serabyn and Lacy (1985) show regular variations in velocity along most parts of these structures. In particular, the velocities in the western arc are well matched by a circular orbit about the center, whereas the northern arm can only partially be described as gas in circular orbit. Two important velocity anomalies are (1) the presence of a second highly blueshifted component at the position where the bar intersects the western arc and (2) a steep velocity gradient from +270 to −270 km s\(^{-1}\) at a point on the bar near to where it appears to cut across the northern arm.

Previous studies of Quinn and Süssman (1985) proposed that the “western arc” and “northern arm” of ionized emission on 2 pc scales could be the trail of a tidally disrupted cloud, whose gas spirals into the center as it flows through a surrounding viscous medium. Their interesting numerical calculations show that while the trajectories of this gas may alternately converge and diverge several times, there is no possibility of the above mentioned “braided” gas motions. By contrast, this feature about the observations is readily explained in our model if we accept the idea that the loop has a fairly strong toroidal field. Recent infrared line polarization data on this scale suggests the existence of a 10 mG field (Aitken et al. 1986) which would be dynamically important. While the calculations of Quinn and Süssman (1985) can, in principle, explain the western arc and northern arm velocities, the large velocities on the bar cannot be due to infall in their model. Very recent observations seem to have shown that the velocity structure is even more complex, with, locally, velocities much higher than 300 km s\(^{-1}\), that makes the purely gravitational interpretation of these motions difficult.

A distinct feature of this “spiral” is the abrupt decrease of radio flux going south from the bar/western arc intersection. The sense of galactic rotation is toward us along the western arc, and away on the northern arm at a rotation speed of order 100 km s\(^{-1}\).

ii) Molecular Torus or Disk

The ionized gas in the western arc, and perhaps the northern arm, is associated with a torus of molecular gas. Shocked molecular hydrogen emission from this torus indicates that the entire structures must be quite disturbed (Gatley et al. 1985). The torus is also observed to be highly disturbed in a transition associated with HCN (Güsten et al. 1986), showing full width half-maximum line widths as much as $\sim 55$ km s\(^{-1}\) (a significant fraction of the rotational velocity). If this is “turbulence,” then it would dissipate in $10^7$ yr in the absence of a source. The effective inferred turbulent pressure is $P_{\text{turb}} \sim 1 - 2 \times 10^{-6}$ ergs cm\(^{-3}\). Other characteristic pressures due to radiation from the central source, the Sgr A H ii region, and a mass outflow in a wind, fail by two orders of magnitude to account for $P_{\text{turb}}$. The field strengths deduced by Aitken et al. (1986), on the other hand, provide magnetic pressures of $\sim 4 \times 10^{-6}$ ergs cm\(^{-3}\), more than enough to account for the strong torus perturbations. Genzel et al. (1985) made an [O ii] study of this region and concluded that the mean density of the torus is $n_H = 10^3$ cm\(^{-3}\) at a temperature of $\sim 3000$ K. They infer a rotation velocity of $102 \pm 10$ km s\(^{-1}\) at $R = 2$ pc, implying an enclosed mass of $(4.8 \pm 1.0) \times 10^6 M_\odot$. Additional constraints on the gravitational potential over these scales was obtained by mapping in the [C ii] 158 $\mu$m fine structures line (Lugten et al. 1986). We adopt the best mass model deduced by these authors, although gas and stellar velocity data are not yet in complete agreement (Sellgren et al. 1987). This model, on the 1–10 pc scale, is a superposition of two components:

\[
\begin{align*}
&\left\{ 2 - 4 \times 10^6 M_\odot \right\} \quad \text{(point mass)} \\
&\left\{ M_\bullet (r) = 1 - 1.5 \times 10^6 M_\odot r_{\text{pc}} \right\} \quad \text{(isothermal star cluster)} \\
&\text{for } 10 \leq r \leq 100 \text{ pc (Lugten et al. 1986, Fig. 7)}
\end{align*}
\]

The rotational velocity then scales as $v \propto r^{1/2}$ in this region.

d) Subparsec Scales

An important asymmetry in the heart of the Galactic nucleus is the apparent 1′–2′ separation (see Lo 1984) between the compact VLBI source Sgr A* that seems to be the true center of the Galaxy (Backer and Sramek 1987) and the star cluster around IRS 16. This, however, is still debated (Lacombe et al. 1987). The VLBI source has a size of 5 × 10^{-3} cm and a radio luminosity of $2 \times 10^{26}$ ergs s\(^{-1}\).

The proper motion of Sgr A* has been shown to imply an upper limit to the projected velocity smaller than 40 km s\(^{-1}\). The broad 2.06 $\mu$m He i line at $\Delta v = 1500$ km s\(^{-1}\) discovered by Hall, Kleinnann, and Scoville (1982) using a 3′8 aperture centered on IRS 16 indicates that high-velocity gas motions does occur (see also Geballe 1987).

Having reviewed the key aspects of Galactic center gas dynamics that any detailed model should address, we now state our basic assumptions.

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MAGNETIC LOOP MODEL

III. ASSUMPTIONS AND BASIC PICTURE

Our unifying scheme for structure on sub-GCL scales rests on three assumptions:

1. The GCL is a discontinuity. It separates cool atomic and molecular gas from the hot inner cavity of the GCL. The GCL is strongly magnetized with a poloidal field largely perpendicular to the galactic plane. Several mechanisms could explain how this lobe formed. One possibility is that a starburst occurred in the Galactic center ~10^7 yr ago (Lebofsky, Rieke, and Tokunaga 1982). Supernova explosions from this burst could explain the overall shape of the GCL (Sofue 1984) and its formation in 2 x 10^6 yr. Such events could also explain the diffuse X-ray emission discussed by Watson et al. (1981) since the cooling time of the hot gas is ~6 x 10^7 yr. Our model, however, suggests that a wind should flow out of the GCL. It could be heated by coronal-like mechanisms (§ VI) and may be energetic enough to create a “cavity” like the GCL in ~10^7 yr too.

2. Filamentary structures inside the GCL are associated with magnetic loops. The radio bridge on 30 pc scales, the protrusions of Sag A West at 10 pc, possibly even the bar feature on 1 pc scales, and as yet unresolved subparsec structures are then regarded as similar entities. Their interaction with the GCL and molecular torus can account for the observed radio and line emission. Those loops which expand primarily in equatorial directions produce the radio arc and bridge morphology revealed by the high-resolution VLA observations.

3. The loop generator on subparsec scales produces enough magnetic flux so that at least some detached loops expand out to 30 pc scales and beyond. The only requirement is that the seat of magnetic activity be associated with significant shearing motions. The generator could emit loops in all directions, and, in fact, the structure of Sgr A West is evidence that isotropic loop shedding occurs. Loops are expelled recurrently at very roughly the rotation period of the emitting body.

Expanding loops will interact with (a) the molecular torus at 2–5 pc and (b) the GCL as discussed in § V and VII.

Expanding magnetic loops collide with the GCL resulting in particle acceleration and bulk heating of the GCL gas. Molecular gas is pictured to reside just outside the GCL. We present an organizing cartoon of our model on Sgr A/GCL scale in Figure 1. Having stated our basic assumptions we turn to a derivation of our model equations.

Fig. 1.—Illustration of structure on 5–100 pc scales in the Galactic center. The GCL is a cylindrical shell separating an internal hot medium from an external cool, neutral, and probably molecular gas. The GCL is threaded by poloidal magnetic field lines. Dense molecular clouds may have formed in the Galactic plane exterior to the GCL out of swept-up material. Magnetic loops are generated on subparsec scales and are largely trapped by the galactic potential on 5–10 pc scales, forming the radio structure Sgr A. Energetic loop eruptions propagate to larger scales. Their collisions with the GCL result in Alfvén wave and energetic particle production on the GCL which produces the “radio arc.” The “bridge filaments” are simply those portions of the expanding loops which have not as yet merged with the GCL. The dissipation of magnetic energy due to shearing of loops near the central body drives a wind out of the Galactic center which could have created the cavity inside the GCL. The merging of a loop with the rotating GCL produces a wakelike magnetic disturbance which accounts for the existence of polarized lobes of emission and a component of the magnetic field in the line of sight of the observer.

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IV. A SIMPLE MODEL FOR LOOP GENERATION AND DYNAMICS

a) Solar Analogy
Loop ejection by a magnetically active object is observed on the Sun, which expels so called “coronal mass ejections” or “transients” (Wagner 1984). These probably are loops or bunches of loops and propagate out to large distances. They erupt from regions on the Sun’s surface which have previously been in quasistatic equilibrium, (Hildner et al. 1976; Munro et al. 1979) when the quasi-static MHD equilibrium of the corona has been driven to the point of loss of equilibrium by slowly evolving boundary conditions (Heyvaerts 1979a, b; Zwingmann 1987). For a complete analysis of this see also Low (1977), Heyvaerts et al. (1982), Aly (1984), Birn and Schindler (1981), and Hood and Priest (1979). There is considerably evidence that the Lorentz force acceleration continues during the expansion (Mouschovias and Poland 1978; Anzer 1978). The nature of the force pushing it outward is certainly magnetic, but might arise from the interaction of the loop current with the magnetic field it self-creates, as Anzer proposed, or from the so-called melon-seed force associated with the gradient of some magnetic field external to the ejected mass (Pneumann 1980).

b) Coronal Transients in the Galactic Center
We assume the prime origin of magnetic features to emanate from some central differentially rotating engine hereafter referred to as “the rotor.” A sketch of the generation and detachment of magnetic loops from the rotor is shown in Figure 2, and is conceived as essentially similar to what...
happens on the Sun. The only requirements of the model here are that the object rotates or has significant shear motion and is threaded by substantial magnetic flux. An obvious possibility would be an accretion disk around a black hole or a flattened body. A massive cloud undergoing significant shearing would do.

The evolution of the loop after detachment is dictated by the expansion force due to current flowing in the loop, which decrease as $1/r^2$, where $r$ is the loop radius. The retarding agents of background gravitational potential and drag forces on the X-ray emitting medium are also important.

c) Model and Assumptions

We adopt Anzer’s (1978) view with some modifications. The Galactic gravitational potential does not scale as $1/r$ on the 100 pc scale. We assess the order of magnitude of drag forces, and, although we find that they are weak, we include them in the numerical calculation. Our loops are actually rotating. We neglect drag torques and assume that angular momentum is redistributed almost instantaneously along the loop, so that it remains planar. Rotation is then fixed by global angular momentum conservation, so that loop’s rotation slows down as it expands. This rigidity assumption is consistent as long as the loop’s internal Alfvén speed is much larger than both the expansion speed and the rotation speed. For typical velocities of 40 km s$^{-1}$ and bridge filament densities of 10$^2$ cm$^{-3}$, this requires a minimum field strength in the bridge of 200 µG. The loops are stable against sausage instability since $B_2^2 > 1/2 B_0^2$, and, when they detach from their source, they are on the verge of kink instability since the eruption condition (Hood and Priest 1980) is actually almost the same as the kink instability condition. This actually may be the cause of detachment by loop buckling as illustrated in Figure 2. The process of detachment is compatible with current ideas concerning flares and erupting transient structures on the Sun (Kopp and Pneuman 1976; Anzer and Pneuman 1982) and may have been observed there (McQueen 1980; Illing and Hundhausen 1983).

Mass-carrying loops are ejected away from their emitting body during the expansion phase, while they are still attached to it, and gain global linear momentum by that time. Loop propagation is retarded by two forces, namely aerodynamic drag by the hot, possibly X-ray emitting gas, filling the GCL; and the gravitational field of the Galactic center. Of these two, gravitational forces acting on the loop can be estimated using the discussion of § IIc(ii).

Our loop model is then reduced to one with three degrees of freedom: the loop radius, $r$, the loop center distance to the Galactic center, $R$, and an angle specifying the angular position of the loop, $\theta$. The latter can be obtained from global angular momentum conservation. The equations for $r$ and $R$ can be obtained from suitable averages on the system of forces acting on the loop. The result depends somewhat on the distribution of mass along the loop that need not be uniform, nor constant in time since gravity drains loop matter down toward the center. We idealize this situation by writing down equations of motions for the top and bottom of the loop. Consider pieces of equal length but with differing mass per unit length, $\mu_1$ and $\mu_2$ (index 1 is for top and 2 for bottom):

$$\dot{R} + \dot{r} = \frac{f(r)}{\mu_1} - g(R + r) - \frac{C_D}{2\mu_1} \rho_s a(r)(\dot{r} + \dot{R})^2 ,$$

$$\dot{R} - \dot{r} = \frac{f(r)}{\mu_2} - g(R - r) - \frac{C_D}{2\mu_2} \rho_s a(r)(\dot{R} - \dot{r})^2 .$$

We have neglected centrifugal forces. During the short initial period of loop attachment, we may consider that $\mu_2 = \infty$. The solution of the second equation with initial conditions $r = R = \dot{r} = \dot{R} = 0$ is then obviously $r(t) = R(t)$. Inserting this in the first equation, we recover Anzer’s equation. During the period when the loop has detached, equations (4.4a) and (4.4b) apply with initial conditions at detachment $r = R = r_0$, $\dot{r} = \dot{R} = 0$, and $r_0$ calculated from the preceding phase. We assume $\mu_2$ to be still somewhat larger than $\mu_1$ in this detached phase, so that $\dot{R} - \dot{r}$ remains much less than $\dot{R} + \dot{r}$. This is because $1/\mu_2 < 1/\mu_1$ and because $g(R - r)$ goes to zero for $r \to R$. With this approximation, $R \approx r$ and the motion does not differ much from the preceding phase. The apex motion equation is

$$2\dot{r} = \frac{\rho_s^2}{\mu_1 4\pi r^3} + g(2r) - \frac{C_D}{2\mu_1} \rho_s a(r)(2\dot{r})^2 .$$

d) Loop Dynamics

We transform to a dimensionless form by choosing a reference radius $r_*$, 2 pc say, and a reference mass $M_*$, which is the one which is enclosed in the sphere of radius $r_*$. According to Genzel et al. (1985), $M_* = 4.8 \times 10^6 M_\odot$. The associated time and velocity unit are

$$t_* = \left( \frac{r_*^3}{G M_*} \right)^{1/2} = 1.9 \times 10^4 \text{ yr} ,$$

$$v_* = \left( \frac{G M_*}{r_*} \right)^{1/2} = 10^2 \text{ km s}^{-1} .$$

where $v$ is the relative velocity to the ambient medium and $C_D$ is a drag coefficient approximately equal to 0.3 (Parker 1975). We neglect the loop buoyancy force. Finally, the gravitational deceleration $g$ upon the mass-carrying loop can be estimated using the discussion of § IIc(ii).
Let

\[ x = \frac{2r}{r_0} \quad \text{and} \quad \tau = \frac{t}{t_0}, \quad (4.7) \]

In these units, the molecular ring is at \( x = 1 \) and \( r_0 \) is the free-fall time at this distance, and the GCL wall is at about \( x = 15 \). We put

\[ m_i = 2\pi r_i \mu_1 \quad (4.8) \]

and consider \( m_i \) as constant during the motion. We normalize the gravitational acceleration to \( GM_*/r_0^2 \), defining \( \psi(x) \) by

\[ g(x) = \frac{GM_*/r_0^2}{r^2} \psi(x). \quad (4.9) \]

Adopting Lugten et al.'s (1986) model, \( \psi(x) \) may be written, using equation (2.5) as

\[ \psi(x) = \lambda_{gal} + \lambda_{clus} \frac{1}{x} + \lambda_{comp} \frac{1}{x^2}, \quad (4.10) \]

where \( \lambda_i = M_i(r_0)/M_* \) and \( \lambda_{gal} + \lambda_{clus} + \lambda_{comp} = 1 \). Likely values for the \( \lambda_i \)'s are \( \lambda_{gal} = 0.08 \) and \( \lambda_{clus} = \lambda_{comp} = 0.46 \) for the case of a massive black hole (see eqs. [2.5a] and [2.5b]). The GCL wall is at about \( x = 15 \) in these units. Equation (4.5) may then be written in dimensionless form as

\[ \frac{d^2x}{dt^2} = \gamma_M - \psi(x) - \gamma_p \frac{x^{n+1}}{x^n} \frac{dx}{dt}, \quad (4.11) \]

where the variation of loop cross-sectional radius has been generalized to scale as \( x^{n+1} \). As discussed before, \( n = 0 \) is likely. Coefficients \( \gamma_M \) and \( \gamma_p \) are defined by

\[ \gamma_M = \frac{2\phi^2}{kGM_*m_1}, \quad \gamma_p = C_D \frac{\rho_v a_* r^2}{2m_i}; \quad (4.12) \]

\( \gamma_M \) is 4 times the ratio of the magnetic energy stored in the loop circuit, to the gravitational potential energy, \( \gamma_p \) measures drag effects and is proportional to the ratio of swept-up X-ray gas mass to loop mass. With loop density \( \rho_{loop} = 4 \times 10^3 \text{ cm}^{-3} \) (Eckers et al. 1983) and \( \rho_v \approx 1 \text{ cm}^{-3} \) (Watson et al. 1981), \( \gamma_M \) is \( 2.25 \times 10^{-3} \) with our values of \( r_0 \) and \( a_* \). So drag effects will be small, and they affect the motion only at large distances. By ignoring drag effects, it is readily seen (eqs. [4.10] and [4.11]) that loops cease accelerating when they reach typical scales of

\[ x_c \approx \left( \frac{\gamma_M - \lambda_{comp}}{\lambda_{clus}} \right), \quad (4.13) \]

where it is assumed that \( \lambda_{gal} \ll \lambda_{clus} \). Since \( \gamma_M < 1 \), \( x_c < 2.2 \) with our set of \( \lambda_i \)'s. Thus we expect that loops all cease accelerating by the time they reach scales of order 1 pc. Loop expansion is strongly retarded on small scales by the presence of a compact source, and in fact \( \gamma_M > \lambda_{comp} \) is a constraint for effective loop acceleration.

Ignoring drag, equation (4.11) is readily integrated, giving

\[ \frac{v^2}{2} = \left( \frac{\gamma_M - \lambda_{comp}}{x_0} \right) \left( 1 - \frac{x_0}{x} \right) - \lambda_{clus} \ln \left( \frac{x}{x_0} \right) - \lambda_{gal}(x - x_0), \quad (4.14) \]

where an initial condition, \( v = 0 \) at \( x = x_0 \) has been employed. Although acceleration ceases early, mass-loaded loops may expand up to \( x_1 \), where \( x_1 \) may be evaluated in the limit \( x_1 \gg x_0 \) as

\[ x_1 = \left( \frac{\gamma_M - \lambda_{comp}}{\lambda_{gal}} \right) \frac{1}{x_0} < \frac{6.75}{x_0}, \quad (4.15) \]

where the latter inequality arises because \( \gamma_M \) can attain a value no larger than 1. If loop are to expand far behind the scale of Sgr A West, the source region must be on subparsec scale \( x_0 < 1 \). Loops anchored in the molecular torus at \( x_0 = 1 \) \( (r_0 \approx 2 \text{ pc}) \) will not reach much farther away than 13 pc, which is, remarkably, the size of Sgr A West radio source (see § VI). As an example, loops on 100 pc scales \( (x_1 = 50) \) would require the source to be at \( x_0 \approx 0.135 \) \( (r_0 = 0.27 \text{ pc}) \). Effects of drag will tend to require slightly smaller regions than this. However, \( x_1 \) is only a fiducial maximum size for given mass-loading of loops. If the mass in the loops manages to cool, it drains back to the portion of the loop closest to the source. This frees the apex to undergo yet more expansion. It is clear that the dynamics of matter along the field lines must be included for this later evolution.

The constraints on the source of the loops arise (a) from the condition that the source magnetic field energy density does not exceed the gravitational energy density, that is \( \gamma_M < 1 \), say (more rigorously, \( \gamma_M < 4 \)), and (b) loop expansion can occur at all, that is \( \gamma_M > \lambda_{comp} \).

\[ 1 > \gamma_M > \lambda_{comp}. \quad (4.16) \]

This may be made more physical by expressing the flux of one loop in terms of the maximum magnetic flux that the source object would be able to gravitationally bind. For flat sources, this is

\[ \phi_0 = \left( \frac{9\pi^2}{10} \right) \frac{G}{M_s} \left( \frac{1}{2} \right)^{1/2} M_s \times 1.54 \times 10^{36} M_{s6} M_{x6} \quad (4.17) \]

where \( \phi_{s6} = (M_s/10^6 M_\odot) \). We scale the flux through the loop, \( \phi_s \), by a parameter \( \zeta \) defined as

\[ \phi_s = \phi_0 \zeta \quad (4.18) \]

The constraint is then

\[ 1 > 3.78 \left( \frac{\zeta - 3 M_{s6}}{m_2} \right) > 0.46, \quad (4.19) \]

where we took the maximum loop mass to be \( m_2 = m_{i2} \times 10^2 M_\odot \) and have put \( \zeta = \zeta / 10^{-3} \). The total number of loop eruptions \( N \) is limited by \( N\phi < \phi_0 \), or

\[ N \zeta^{1/2} = 32 \zeta^{-1/2}. \quad (4.20) \]

Therefore, a total mass of \( N m_{i2} \geq 3 \times 10^3 M_\odot \) could be carried away from the central source body, which is an insignificant portion of its total. Nonetheless, this is a high fraction of the mass in the torus.

The magnetic field that must be associated with the source object may be estimated from equation (4.19), and the constraint that bridge filaments arise from loops expanding away from this object (eq. [4.17]). Thus, an upper limit to the field strength at the source is

\[ B_s \leq \frac{\phi_s}{\pi s^2} = 0.76 M_{s6} \left( \frac{r_s}{0.27 \text{ pc}} \right)^{-2} \quad G \quad (4.21) \]

if eruptions powerful enough to produce the large loops reaching to 100 pc are to be produced.
Numerical solutions to equation (4.11) with \( n = 0 \) were found using a standard fifth-order Runge-Kutta method on a VAX 8600 computer. The observations of recombination line widths at each scale can be used to constrain the parameters of our model. As an example, while velocities of order 300 km s\(^{-1}\) could be tolerated on scales \( \leq 1 \) pc, the projected velocities associated with the bridge filaments (30 pc scale) should be no more than \(~100–150\) km s\(^{-1}\). Calculations of loop expansion velocity as a function of loop size are shown in Figures 2 and 3. All loops were taken to start at the scale \( x_0 = 0.05 \) (\( r_0 = 0.1 \) pc). The curves in Figures 3a and 3b are plots of loop velocity as a function of size calculated for the galactic potential (2.5) modified from Lugten et al. and in which a black hole of mass \( M_h \sim 10^6 M_\odot \) is present. Figures 4a and 4b, on the other hand, show loop evolution for \( \gamma = 0.01, \) and \( \lambda_{\text{clus}} = 0.91, \) i.e., a low-mass hole \( M_h \sim 10^4 M_\odot. \) The results clearly demonstrate that the Kepler potential of a black hole strongly retards loop motion because of the \( r^{-2} \) nature of the radial Lorentz forces driving loop expansion.

A second effect apparent in the numerical results is that higher peak velocities are reached for loops with larger magnetic energy densities (measured by \( \gamma_M \)). The effects of drag are not seen on subparsec scales, since the velocity of a loop at its peak value is not visibly affected by changing \( \gamma_D \) (compare the curves in Fig. 4b with respect to 4a). Velocities at 30 pc scales (\( x = 15 \)), however, are quite markedly affected by drag effects in that for the same \( \gamma_M, \) changing \( \gamma_D \) from 0.002 to 0.01 reduces these speeds from 184 km s\(^{-1}\) to 32.5 km s\(^{-1}\) (Fig. 3) in the massive halo model (\( \gamma_M = 0.8 \) curves) and from 110 km s\(^{-1}\) to 25 km s\(^{-1}\) in the low-mass hole model (\( \gamma_M = 0.4 \) curves, Fig. 4).

For both high- and low-mass hole models, it is clear that individual loops must have magnetic energy densities comparable to gravitational potential energy density. In the massive hole case, the curve which best fits observational constraints is \( \gamma_M \sim 0.8, \) \( \gamma_D = 0.002; \) peak speed 318 km s\(^{-1}\) at \( x = 0.2 \) (\( r = 0.4 \) pc); speed at 30 pc 184 km s\(^{-1}\). For low-mass holes (\( M \sim 10^4 M_\odot \)), the numerical results show the best model is \( \gamma_M \sim 0.4, \gamma_D \sim 0.002; \) peak speed, 313 km s\(^{-1}\). These models provide insight into how significant momentum input can be...
transferred to the GCL to produce significant shocks and Alfvén wave heating, as will be discussed in § VII.

Coronal transients of lower magnetic energy than those discussed above, could create the structure of Sgr A. The numerical results in Figure 2 as an example show that loops with $0.555 < \gamma_M < 0.7$ slow to a stop on scales typical of Sgr A. Since we expect, in analogy with the Sun, many more lower energy events, the assimilation of Sgr A with a dense cluster of loops is very natural as loops become trapped by the Galactic potential.

We conclude this section by emphasizing that high expansion speeds on subparsec scales are a natural outcome of our picture, and a gravitational interpretation of these velocities is unnecessary.

V. LOOP-TORUS INTERACTION

Loops expanding from subparsec scales will encounter the 2 pc molecular ring. A super-Alvénic shock will form for high $\gamma_M$ loops and strands of the braided loop field will reconnect with toroidal field in the torus. The main feature of the observations that need to be explained are (1) the extremely sharp velocity gradient ($\pm 260 \text{ km s}^{-1}$), where the east-west “bar” cuts the northern arm; (2) the ring of high-luminosity ionized emission on the torus; (3) a continuous heat source for the ionized and molecular ring emission; (4) molecular line width of 55 km s$^{-1}$.

Figure 5 shows how we envisage the east-west “bar” to be a portion of a magnetic loop which extends to the northwest, possibly out to 5–10 pc scales: the interaction of this loop with the torus field is driving the high-velocity gas motions and shocks the surrounding molecular material. We show below that these processes can account for many of the observed properties of gas associated with the torus and “bar.”

a) Reconnection at the Loop-Torus Interface

It is known that high-velocity gas motions in the immediate vicinity of a reconnection point are driven at nearly the Alfvén speed (Petschek 1964). Associated particle acceleration is often observed (Heyvaerts 1981). These shocks will produce nonthermal emission knots, where field lines of the loop and molecular torus have merged and material is flowing away at high speed from their center which is at zero velocity. The nonthermal emission knot V7 seen at the position of the steep velocity gradient (Brown and Liszt 1984) may be one. The loop’s Alfvén velocity is, using the ionized gas density of...
Fig. 4.—Same as in Fig. 3, except the mass of a central black hole is taken to be only $10^4 M_\odot$.

Making some allowance for projection effects, a reconnecting loop field of $10^{-2}$ G at the 2 pc scale could account for the Ne ii high velocities. This provides a nongravitational explanation for these and the observed sharp gradient. A reconnection event should also occur where the east-west “bar” intersects the western arc (Fig. 5). The high-velocity feature there ($-160$ km s$^{-1}$; Ekers et al. 1983), where one otherwise anticipates much lower rotation speeds, suggests this.

b) Shocks at the Loop-Torus Interface

Sufficiently magnetized loops will strike the torus at super-Alfvénic speeds and shock it. These one-dimensional loops will produce transverse velocities at the bow shock of order $v \approx v_{\text{shock}}/M_\Lambda$, where $M_\Lambda$ is the Alfvén Mach number. Alfvén speeds of 300 km s$^{-1}$ (eq. [6.1]) and low Mach numbers ($M_\Lambda \approx 1, 2$) could then also produce the observed velocity discontinuity. The interaction region should be small, as is observed, and most likely associated with the shock interaction of the expanding loop with some particular flux tube of the torus. Particle acceleration occurs in such shocks (Blandford and Ostriker 1978; Achterberg and Norman 1980), and we note that reconnection and shocks can, of course, coexist.

c) Ring Emission

Hydromagnetic waves and accelerated particles locked in them will be carried downstream from the prime interaction region by the rotating torus provided the Alfvén velocity in the neutral material is smaller than the torus rotation speed. Adopting Genzel et al.’s (1985) density estimate, we find

$$V_{A,\text{torus}} \approx 60(B_{\text{torus}}/10^{-2}\text{ G})(n_{\text{torus}}/10^5 \text{ cm}^{-3})^{-1/2}\text{ km s}^{-1}$$

which is less than the torus rotation speed of 100 km s$^{-1}$. The loop does not penetrate the torus, however. For this to occur the ram pressure $\rho V_{\text{exp}}^2$ would have to greatly exceed $B_{\text{torus}}^2/8\pi$. Hence this requires $V_{\text{exp}} \sim 300$ km s$^{-1}$, whereas these velocities are roughly the same. Therefore the expanding loop merely glides on the torus. Part of it will merge into it by reconnection on the interaction time scale.
The induced disturbances move downstream at a speed of 160 km s\(^{-1}\) and dissipate, heating and ionizing the gas. The extent of ionized torus emission, \(s_{\text{ion}}\), is determined by the shorter of the interaction time or of the wave damping time (\(\approx t\)) as follows:

\[
s_{\text{ion}} \approx (v_{\text{tot}} + v_{A,\text{torus}}) t = 3 \left( \frac{(v_{\text{tot}} + v_{A,\text{torus}})}{160 \text{ km s}^{-1}} \right) \left( \frac{t}{1.9 \times 10^4 \text{ yr}} \right) \text{ pc}.
\]  

(5.3)

Thus, for \(t \sim 2 \times 10^4 \text{ yr}\), the ionized emission would extend to a 3 pc, or one-fourth of the ring's perimeter. This is the length of the western arc and northern arm. A typical value for the interaction time is \(t_{\text{int}} = t_{\text{torus}}/v_{\text{exp}} = 0.7 \times 10^4 \text{ yr}\) at 2 pc if \(v_{\text{exp}} = 300 \text{ km s}^{-1}\).

d) Ionization and \(\text{H}_2\) Excitation

A fraction \(\epsilon\) of the mechanical and magnetic energy of the loop is deposited into the torus. The energy input by a loop of mass \(m_l\) interacting for a time \(t_{\text{int}}\) is

\[
L_{\text{mech}} = 3.0 \times 10^{37} \left( \frac{m_l/20 M_\odot}{v_{\text{exp}}/300 \text{ km s}^{-1}} \right)^2 \left( \frac{t_{\text{int}}}{2 \times 10^4 \text{ yr}} \right) \text{ ergs s}^{-1}.
\]

(5.4)

Linear Alfvén wave damping mechanisms are usually inefficient at heating gas. However, turbulent cascades set off by those waves as they propagate into the inhomogeneous torus material lead to much more efficient heating (for a study of these processes in solar coronal heating context see Heyvaerts and Priest 1983 and Hollweg 1983). Dissipation at this maximum rate can be achieved in a few wave periods, i.e., \(t_{\text{damp}} \approx\) several \(\times 10^4\) yr, which is the period of Alfvén waves with wavelength comparable to the injection scale (~1 pc).

The averaged power input over many loop collisions is of order \((t_{\text{int}}/t_{\text{rec}})L_{\text{mech}}\), where \(t_{\text{rec}}\) is the recurrence time for loop eruptions. Since there appears to be only one major loop-torus collision presently we expect \(t_{\text{rec}} \approx t_{\text{int}}\).

Molecular hydrogen line emission mentioned above accounts for a power loss from the torus of \(\sim 2 \times 10^{36}\) ergs s\(^{-1}\). This can be accommodated by the calculated power input if both \(\epsilon\) and \(t_{\text{int}}/t_{\text{rec}}\) are of order unity.

The ionized gas temperature that can be reached by radiating some \(10^{36}\) ergs s\(^{-1}\) in a volume of 8 pc\(^3\) with a density of \(10^3\) cm\(^{-3}\) is \(\sim 3000\) K. This was deduced by balancing the mechanical energy input with optically thin radiative cooling (Cox and Tucker 1969).

We conclude that mechanical energy transfer to the molecular torus by expanding magnetic loops is a sufficient source of...
Fig. 5.—Interaction of a rapidly expanding magnetic loop with the molecular torus on 2 pc scale accounts for the morphology of ionized gas emission seen on this scale. The east-west “bar” is actually a portion of an expanding loop. An MHD shock occurs where the loop encounters the torus. Reconnection of loop with torus field produces localized high-velocity gas motions where the intersection occurs. The torus rotation speed is larger than the Alfvén velocity in the torus, so that hydromagnetic waves are carried downstream by the torus. This accounts for the sharp difference in radio continuum flux along the ionized torus at the two points of intersection with the bar feature. Dissipation of the hydromagnetic waves as they propagate along the torus can heat gas to the temperatures inferred from the radio observations.

Energy. An ultraviolet flux can also add to the energy input, but any significant flux will create a large ionized cavity, which is not observed.

e) Lumpy Torus Structure

Finally, let us ask whether our loop shocks can account for the peculiarities of the molecular gas in the torus. Two main observational features of the torus are (a) broad HCN line widths of $\Delta v \approx 55$ km s$^{-1}$ and (b) highly clumped structure.

Equation (6.2) shows that these line widths are sub-Alfvénic in the torus. Therefore, the magnetic energy density would be sufficient to confine the turbulent gas. Since the ratio of magnetic to rotational energy densities in the torus is $B^2 / 8\pi \mu I_{rot} \approx 0.36$, the expected magnetic field of $10^{-2}$ G should be regarded as dynamically important. In particular, it could resist shearing of the gas clumps by differential rotation. This is similar to the idea that supersonic line widths in Galactic molecular clouds can be supported by Alfvén waves (Arons and Max 1975). Balancing the power input $L_{mech}$ by the rate of decay of Alfvénic turbulence,

$$L_{mech} = \frac{m_{torus}(\Delta v)^2}{\tau_{damp}},$$

and solving for $\Delta v$, using equation (5.4), gives an estimate of the expected turbulent velocities:

$$\Delta v = 42.5 \left( \frac{\tau_{damp}}{10 \tau_{rec}} \right)^{1/2} \left( \frac{m_{loop}}{20 M_\odot} \right)^{1/2} \times \left( \frac{10^4 M_\odot}{m_{torus}} \right)^{1/2} \left( \frac{v_{exp}}{300 \text{ km s}^{-1}} \right) \text{ km s}^{-1}. \quad (5.6)$$

This shows that the observed turbulent velocities could in principle be explained. Güsten et al. (1986) argue that the torus structure would smear itself out and invade the region inside 2 pc, on a $10^6$ yr time scale without some other support. This creates no difficulty for a magnetized torus model since the various clouds can be held together by a large enough magnetic field as said above and loop-torus collisions can occur frequently enough to maintain turbulent agitation in the torus.

f) Mass and Angular Momentum Balance

We have shown in § IVd that a maximum of $3 \times 10^3$--$10^4$ $M_\odot$ could be deposited on the torus in $10^7$ yr. This mass injection has significantly less specific angular momentum than the torus has. The torus mass could only originate from this deposition if the seed material had been of very high specific angular momentum (which is unlikely), or if some spin-up mechanism is acting on freshly deposited material. One could think of dynamic friction with the ambient star cluster.
According to Tremaine, Ostriker, and Spitzer (1975) the associated time scale \( t_p \) is
\[
 t_p = \frac{\sqrt{2}}{\sqrt{3}} \frac{1}{4n^2 M_\odot^{3/2}},
\]
where \( M_\odot \) is the cloud mass, \( \sigma \) the velocity dispersion, and \( \rho_* \) the local star mass density. Adopting \( \sigma = 100 \text{ km s}^{-1} \), \( M_\odot = 10^{-2} M_\odot \), and the model (eq. [2.5a]) for the cluster mass distribution gives a time of \( 2.5 \times 10^8 \text{ yr} \). Special conditions associated with nonaxisymmetric potential such as bar could, in principle, give spin-up.

The deposition of angular momentum--poor material in the torus-expanding loops causes a retarding torque on the torus. The rate of change of specific angular momentum \( j \) associated with direct mass deposition, assuming zero specific angular momentum for the loop material, is \( -j/\Omega M \). This force alone acts to drag the torus material to the center in a mass deposition time scale of some \( 10^7 \text{ yr} \), that is of order \( 10^2 \) rotation periods.

Let us now go to slightly larger scales, and consider the structure of Sgr A in the context of our theory.

VI. SGR A AS A CORONA

Our model suggests that Sgr A should actually be the magnetized corona of the molecular torus at 2 pc. Magnetic field lines which have reconnected with the torus field become part of the torus field system itself. The differential rotation across the torus is significant, and this results in active field amplification by differential rotation. One can show that this energy input into the loops is ultimately dissipated as heat, which provides a simple model for the Sgr A radio source.

a) Coronal Heating Processes

Heating should result from electric current flowing in the medium as is well documented for the Sun, and this could explain the presence of the X-ray emitting gas, although certainly a more conservative explanation in terms of supernovae heated gas is quite plausible (Ekers et al. 1983). Solar coronal heating has attracted considerable attention in the past few years, and the basic processes seem to be now understood, at least for closed magnetic regions. They involve dissipation of resonant oscillations in inhomogeneous media (Ionson 1978; Heyvaerts and Priest 1983) or resistive turbulent dissipation of DC current (Chiuderi 1981; Parker 1986; Heyvaerts and Priest 1984). Both processes occur simultaneously. The DC one is amenable to numerical estimation without detailed knowledge of the source properties. The heating flux per unit surface of the dynamo object associated with this process (Heyvaerts and Priest 1984; Browning, Sakurai, and Priest 1986) is given by
\[
 F = \frac{f B^2}{16\pi n v},
\]
where \( v \) is the velocity with which footpoints of magnetic lines are sheared at the surface of the driving body, and \( f \) is a geometry-dependent limiting factor, smaller than one. Hence the total coronal heating rate is given by
\[
 H = \frac{\sigma f}{4} B^2 R^2 v ,
\]
where \( \sigma \) is the fraction of the source surface which is magnetized.

The shear velocity is
\[
 v \approx v_{\text{rot}}(\Delta r/r),
\]
where \( \Delta r \) is a characteristic shear length for flux tubes. We adopt \( \Delta r \approx 0.25 \text{ pc} \) since this is the resolved clump scale in the molecular torus, which we take as representative of the flux-tube minor radius. For \( \sigma \)

we adopt the clump area covering factor \( \sim 10^{-1} \). Then equation (6.4) gives the numerical estimate
\[
 H = 1 \times 10^{38} \left( \frac{\sigma}{10^{-1}} \right) f \left( \frac{B_{\text{tot}}}{10^{-2} \text{ G}} \right)^2 \left( \frac{R}{2 \text{ pc}} \right)^2 \times \left( \frac{v_{\text{rot}}}{10^2 \text{ km s}^{-1}} \right) 0.8 \frac{r}{r} \text{ ergs s}^{-1} .
\]

This heating rate is sufficient to account for the total X-ray luminosity of the diffuse component, which is \( 2.2 \times 10^{36} \text{ ergs s}^{-1} \) (Watson et al. 1981).

A similar but much more powerful process should take place in the environment of the rotor. Since we have no direct evidence for its scale, field, or velocity, the estimation is uncertain in that case. Conservatively scaling (7.2), arbitrarily assuming \( BR^2 \) to be the same for the rotor as for the torus (it should be larger for the rotor), and scaling \( r_{\text{rot}} \) according to Keplerian laws, the heating would scale as \( R^{-5/2} \), which means a factor 300 in the heating rate for a reduction by a factor 10 in size.

b) Wind

The reconnection activity in Sgr A will continuously turn part of the closed field lines into open ones when the former reconnect to already open structures. It is possible that the material seen in X-rays is entirely confined in closed loops, although this would require fields even larger than those which would be in pressure equilibrium with the hot medium. If, as is more likely, part of it is connected to open magnetic field lines or is field-free, then the existence of a wind will follow model independently since a \( 10^8 \) K gas cannot be bound in the potential well.

Similarly, the central object itself should possess an extended low \( \beta \) coronal type halo. According to our study of § IV, this region should be pervaded by those weakly magnetized loops which have parameter \( \gamma_{\text{tot}} \) much smaller than 0.5, say.

Let us estimate the wind mass-loss rate blown in the open magnetic configuration which is implied by the observed existence of the 1 cm\(^{-3} \) medium heated to \( 10^8 \) K which emits the diffuse X-rays on the scale of Sgr A. It will be estimated from classical thermal wind theory (Parker 1958). We adopt an isothermal equation of state and spherical expansion model in a gravitational potential \( G(r) \) and define dimensionless variables by
\[
 x = \frac{r}{r_1} , \quad u^2 = \frac{v^2}{(2kT/mp)} , \quad \frac{dG}{dx} = \frac{g(xr_1)}{g(r_1)} , \quad \Lambda = \frac{r_1 g(r_1)}{(2kT/mp)} ,
\]
where \( r_1 \) is a reference distance where the density \( n_1 \) is supposed to be known. We adopt \( r_1 = 1 \text{ pc} \) so that \( x \) is the same as in equation (4.7). The equation for stationary flow is
\[
 \left( 1 - \frac{1}{u^2} \right) \frac{du^2}{dx} = \frac{4}{x} - 2\Lambda \frac{dG}{dx} ,
\]
and its solution is given by
\[
 u e^{-u^2/2} = K e^{\Lambda G(x)} ,
\]
where \( K \) should be chosen so that the solution passes through the critical point (Parker 1958), the position of which is given.
in terms of $\psi(x)$ (eq. [4.10]) by

$$\frac{1}{4} \frac{GM}{r^2} \frac{mp}{kT} x_c \psi(x_c) = 1 . \quad (6.6)$$

Solving this gives $x_c = 1.4 \times 10^{-2}$ and, of course, $u_r = 1$, so that $K$ in equation (6.5) is known. It is noted that $x_c$ is small since $\psi(x_c) \approx 1/x^2$ and $1/4(\frac{GM}{r} mp/kT)$, which is of the order of $\Lambda$, equals $3.1 \times 10^{-3}$. Taking this into account, the dimensionless velocity at the reference level is found to be $4.12$, which means that the flow is largely supersonic there. Knowing the density at this point we obtain the mass-loss rate:

$$M = (n_1 m_p) \left( \frac{kT}{mp} \right) (4\pi r_i^3) \sim 1.54 \times 10^{-3} M_\odot \text{ yr}^{-1} . \quad (6.7)$$

We contend that this is a consequence of the observed X-ray gas. The enthalpy flux of this large wind exceeds the global heating rate (eq. 6.2) associated with the molecular torus. However, as explained above, a much stronger heating rate is expected from the rotor itself which could easily account for a heating rate (eq. 6.2) associated with the molecular torus.

VII. THE LOOP-GCL INTERACTION

Let us return to consider the largest scales characterizing the GCL itself. We have seen that only the most highly magnetized loops manage to expand out to these scales. What sort of interactions can we expect?

A loop expanding from the center has expansion motions of $\gtrsim 50 \text{ km s}^{-1}$ and negligible rotation, having detached from the central object. The loop may penetrate the GCL in this collision because $\rho_i v_i^2$ is larger than $B_{GCL}^2/8\pi$. Actually, with $n_{\text{prop}} = 10^5 \text{ cm}^{-3}$, $B_{GCL} = 250 \mu G$, and $v_{\text{exp}} = 100 \text{ km s}^{-1}$ we get $B^2/8\pi = 2.5 \times 10^{-9} \text{ ergs cm}^{-3}$. $\rho_i v_i^2 = 1.6 \times 10^{-8} \text{ ergs cm}^{-3}$.

a) Reconnection Interaction

The GCL may constitute a rather sharp discontinuity between interior, hot, X-ray emitting gas and exterior molecular dense material. If this boundary is coupled to the Galactic disk material it will rotate at about $v_{\text{rot}} \approx 110 \text{ km s}^{-1}$. The Alfvén velocity in the ionized GCL material is $\sim 180 \text{ km s}^{-1}$ and with these canonical numbers, it is not clear whether a shock will occur or not. If there is one, it will be of low Mach number. Reconnection of the magnetic fields will occur at points where flux tubes from each system make contact. This will produce electric field components parallel to magnetic fields in the reconnection region. These contact zones actually act as an electromotive region driving a perturbation current system. The relevant electric field component in the interaction region is

$$E_{\text{rec}} \approx \frac{v \times (B_1 - B_2)}{c} \approx 0.8 \times 10^{-7} \left( \frac{B_{\text{GCL}}}{250 \mu G} \right) \left( \frac{v_{\text{exp}}}{100 \text{ km s}^{-1}} \right) \text{ statvolt cm}^{-1} , \quad (7.1)$$

where $\phi$ is the relative velocity. The exact value depends on the geometry of the exhaust flow and on the compressibility of the fluid (Petschek 1964; Sonnerup 1974).

When this field acts on a mean free path

$$l \approx 3 \times 10^{13} \left( \frac{T}{10^4 \text{ K}} \right)^{2} \left( \frac{10 \text{ cm}^{-3}}{n} \right) \text{ cm} , \quad (7.2)$$

energies of the order of $10^4 \text{ meV}$ can, in principle, be reached. In reality bulk heating of the plasma will occur, and only a fraction of the particles on the exponential of the distribution will be accelerated to high energies. If 1% of the population is accelerated, one can produce the luminosity of the polarized radio halo by a population of relativistic electrons with Lorentz factors of order $10^3$.

For the appropriate field geometry shown in Figure 6 the accelerated electrons will be injected outward into the polarized lobes in both north and southern hemispheres.

b) Polarized Lobe Emission

The Alfvén speed in the GCL is $\sim 180 \text{ km s}^{-1}$. The time for these waves to propagate a distance of 100 pc, the observed height of the polarized lobe, is $\tau_{\text{prop}} = 5.7 \times 10^5 \text{ yr}$. The polarized nonthermal emission in these lobes arises by radiation of relativistic particles, produced at the reconnection points which propagate with Alfvén waves into the GCL. In a field of $250 \mu G$, radio emission at 5 GHz requires

$$\gamma_{\text{elec}} \approx 2 \times 10^3 , \quad (7.3)$$

and the synchrotron lifetime of these particles is

$$\tau_{\text{syn}} \approx 1.4 \times 10^5 \text{ yr} . \quad (7.4)$$

Thus, $\tau_{\text{syn}}$ is consistently of the same order as $\tau_{\text{prop}}$. The intense polarized spot just north of the bridge/arc intersection marks a point of intense particle acceleration.

Yusef-Zadeh and Morris (1986) argue that most of the arc is depolarized because of intervening gas and only a few polarization points show through "windows." While some of this may be valid, it does not account for the fact that polarized emission strongly peaks near the bridge/arc intersection points. This has a natural explanation in our model. It is possible that the polarized "spot A" (Seiradakis et al. 1985) is a reconnection point of one "helical" filament with the arc.

c) Current Systems

The collision of an expanding loop with the GCL will excite hydromagnetic waves in the GCL. In general, two classes of hydromagnetic waves can be supported near an interface. Body waves, such as ordinary shear Alfvén waves, slow and fast magnetosonic waves, and surface waves (for a thorough discussion, see Wentzel 1978; Ionson 1978; Roberts 1980). If the expanding loop were only to graze the interface, it would act as an emitter of such surface waves. This wave system actually constitutes the current system induced on the GCL boundary by the collision with the loop. The waves form a wake behind each of the two points on the GCL (north and south) where the loop is currently merging with it. The loop rotates in the $\phi$-direction, and the magnetic perturbations communicate the stress from the merging loop to the GCL plasma. The current associated with wave flow (which is all the while being carried along by rotation of the GCL at the rotation speed $v_{\text{rot}}$) is restricted between "Alfvén wings" which are inclined to the GCL field $B_1$ by the Mach angle $\theta_A$. For shear
Alfvén waves, one finds the angle:

$$\tan \theta_\lambda = \left( k_x / k_y \right) = \left( v_{\text{rot}} / v_{\text{A}, \phi} \right).$$

(7.5)

Since the ratio of kinematic and magnetic energy density of the loop relative to the boundary is larger than unity, the wake perturbation becomes very nonlinear. The main effect will be a bending of the expanding loop in the sense of rotation, and deformation of the hydromagnetic flow around the loop. The GCL field between the two penetration points will be stretched.

If the entering loop produces a stagnation point, the field lines at higher Galactic latitudes will stretch at a Mach angle $\theta_\lambda$ with the vertical. At latitudes between these points the field will join the points (or be inclined at $\theta_\lambda$) if the loop plane makes a larger (or smaller) angle than $\theta_\lambda$ to the vertical. The current will flow along these directions.

**d) Rotation Measure**

An observational consequence of the previous subsection is a possible explanation for the polarized emission lobes. Taking $v_{\text{rot}} \sim 110$ km s$^{-1}$, $B \sim 250$ $\mu$G, and $n \sim 10$ cm$^{-3}$, one finds

$$\theta_\lambda = 32^\circ.$$  

(7.6)
The field strength of 250 \( \mu G \) corresponds well with the prediction that \( B \geq 590 \mu G \) if pressure equilibrium between the hot GCL and the magnetized GCL is to be possible. In fact, this suggests that a reasonable estimate for the temperature of the hot gas is \( T_{\text{hot}} \approx (250/590)^{1/2} \sim 0.65 \) or \( 6.5 \times 10^7 \) K. The line-of-sight component \( B \) changes sign between north and south Galactic latitude.

**e) Alfvén Wave Heating and GCL Radio Emission**

Damping of the nonlinear shear Alfvén waves set up on the outer GCL can heat the gas to high temperatures. We evaluate here the maximum heating rate obtained by the damping of the shear Alfvén waves previously discussed. The wave flux is

\[
F_{\text{wave}} = \rho v^2 c_{\text{rot}} \tan^2 \theta_A \approx 3.4 \times 10^{-2} \left( \frac{B}{250 \mu G} \right)^{3/2} n_1^{-1/2} \text{ergs cm}^{-2} \text{s}^{-1}, \tag{7.8}
\]

where we note that the energy density of the waves is \( \rho v^2_{\text{rot}} \) and \( \rho \) is the GCL density. This arises because the perturbed velocity in the GCL due to the deformation is of order \( v_{\text{rot}} \). The volume heating rate due to the dissipation of this wave flux is then

\[
\epsilon_H = \frac{F_{\text{wave}}}{L} = 1.1 \times 10^{-22} \left( \frac{B}{250 \mu G} \right)^{3/2} n_1^{-1/2} \left( \frac{100 \text{ pc}}{L} \right) \text{ergs cm}^{-3} \text{s}^{-1}, \tag{7.9}
\]

where \( L \) is the wave dissipation scale length. Balancing this with optically thin radiative losses (Cox and Tucker 1969; Hildner 1974) gives, for \( T_e \leq 1.5 \), at densities \( n_1 \sim 10 \text{ cm}^{-3} \):

\[
T_{\text{lobe}} = 9000 \text{ K} \left( \frac{B_g}{250 \mu G} \right)^{0.20} n_1^{-0.34} \left( \frac{100 \text{ pc}}{L} \right)^{0.14}, \tag{7.10}
\]

\((T < 1.5 \times 10^4 \text{ K})\),

which is very close to estimates made from the radio data (Sofue 1985).

This heating explains the thermal emission from the entire GCL. The higher brightness of the radio arc is due to higher gas density in this region. Because the brightness of the arc changes sharply as the bridge filaments are crossed, we suggest that the density enhancement arises by compression of the rotating lobe interacting with the impinging loop penetrating the GCL in between the most widely separated interaction points.

This method of heating the GCL implies that the radio emission is a vertical "plume" on a portion of the GCL rather than a limb-brightened shell (e.g., Sofue 1985). The western radio emission ridge should also be such a plume induced by another loop/GCL collision. The detection of "bridge filaments" associated with this emission would confirm this view.

**f) Parallel Radio Arc Filaments**

The presence of any perturbation on the loop boundary can modulate the current system on the GCL. There are two possibilities: Kelvin-Helmholtz instability at the loop GCL interface or Rayleigh-Taylor instability at the GCL interface between the interior, hot, poorly magnetized medium and the external, cool, magnetized gas. Consider first the criterion for Kelvin-Helmholtz instability. In the limit when the loop density exceeds the one in the boundary this is

\[
\frac{\nabla A}{\nabla B} \tan \theta_A < 1, \tag{7.11}
\]

where \( \theta_A \) is the angle between the loop and boundary fluid at their interface, and \( \nabla A, \nabla B \) is defined by

\[
\nabla A, \nabla B = v_{\text{A,loop}} \left( 1 + \frac{B_{\text{GCL}}}{B_{\text{loop}}} \right), \tag{7.12}
\]

Inserting equations (7.5) and (7.6) for \( \theta_A \), we find that the configuration is always stable.

Observations of the GCL boundary suggest that it is concave outward, which implies instability, since the hot gas is on the concave side. This instability develops flute-like perturbations parallel to the GCL field, which in the case of high-density contrast grow in a time

\[
\tau_{R-T} = \frac{1}{v_{\text{A,loop}} \sqrt{k}}, \tag{7.13}
\]

where \( R \approx 30 \text{ pc} \) is the radius of curvature of the boundary, \( k \) is the wavenumber of the perturbation, and \( v_{\text{A,loop}} \) is the thermal velocity in the high-pressure gas. The "effective gravity" associated with this curvature is \( g = v_{\text{A,loop}}^2 / R \). The perturbation scale is the loop thickness \( \theta_l \approx 1 \text{ pc} \).

This estimate for \( k \) gives

\[
\tau_{R-T} = 1.7 \times 10^4 \left( \frac{R}{30 \text{ pc}} \right)^{1/2} \left( \frac{\theta_l}{1 \text{ pc}} \right)^{1/2} \left( \frac{T_e}{10^7 \text{ K}} \right)^{-1/2} \text{ yr}. \tag{7.14}
\]

Since the loop-GCL interaction may have lasted for \( 10^4 \) yr, fluting will be well developed.

The instability causes the undulation of the current carrying boundary, but very little density perturbation. Therefore the radio-emitting region may be pictured as a rippled curtain, which, because of line-of-sight effects appears to have a modulated emission.

**g) Curved Filaments East of the Arc**

Another aspect of the radio arc morphology is the appearance of curved filaments which are observed eastward of the straight parallel main filaments. The eastern extremity of radio emission is the true position of the magnetic loop which has come to rest at the strongly magnetized outer surface of the GCL. The penetration of the loop into the GCL is followed by deflection of the rotating boundary. These curved filaments are just that part of the expanding loops which have already penetrated the boundary.

**h) Threads**

These long thin filaments appear to join the GCL smoothly at galactic latitudes higher than the radio arc. As explained earlier, loop fields reconnect with GCL field lines. Such recon-
networked fields can be pulled out by magnetic tension out of the GCL and account for the threads. Because reconnection is highly localized (Russell and Elphic 1978), only thin strands will be pulled out of the GCL. The high pressure of the hot interior medium will, moreover, confine them strongly.

i) Excitation of Bridge Filaments and Associated Material

Let us consider the thermal properties and energy balance of the filaments. The magnetized loops which we assume propagate in the GCL cavity interact with the ambient medium. The drag force per unit length suffered by a loop expanding at velocity \( v \) in a medium of density \( \rho \) is given by equation (4.13). The associated friction work divided by the loop cross section gives the heating rate that would result if all that energy were to be dumped in the loop alone. In fact, a fraction \( k \) only goes into loop heating, the rest being dumped in the ambient medium. This gives the loop heating rate

\[
E = \frac{C_{D}}{2na} \rho v^3.
\]  

(7.15)

In the X-ray gas, for \( v = 100 \text{ km s}^{-1}, a = 1 \text{ pc}, \) and \( n = 1 \text{ cm}^{-3} \), we find \( E/k = 4.25 \times 10^{-23} \text{ ergs cm}^{-3} \text{ s}^{-1} \). The loop internal temperature is obtained by balancing this with radiative losses. For temperature less than \( 1.5 \times 10^4 \text{ K} \), this gives

\[
E = 1.96 \times 10^{-20} \left( \frac{T}{10^4 \text{ K}} \right)^{7.4} \left( \frac{n_{\text{loop}}}{10^2 \text{ cm}^{-3}} \right)^2 \text{ ergs cm}^{-3} \text{ s}^{-1}.
\]  

(7.16)

We obtain a temperature estimate for \( k = 0.1 \) of \( 3 \times 10^3 \text{ K} \). Where, however, the loop happens to ram into a molecular cloud, a shock will be driven. This makes \( C_{D} \) somewhat larger, and the dependence of Mach number is a bit weaker. The main effect, however, is the large increase in ambient material density. Keeping for simplicity \( C_{D} = \frac{1}{2}, \) we get \( E = 4.25 \times 10^{-19} \text{ ergs cm}^{-3} \text{ s}^{-1} \) for \( v = 100 \text{ km s}^{-1}, a = 1 \text{ pc}, \) and a molecular medium density of \( 10^5 \text{ cm}^{-3} \). The corresponding loop temperature is \( 1.2 \times 10^4 \text{ K}, \) allowing for a slightly larger loop density in the case of shocked loops.

The accelerating loop acts as a piston driven by electromagnetic forces when colliding with the molecular gas. Material will reach velocities essentially equal to that of the loop. This may explain Serabyn and G"{u}sten's (1987a,b) observations that molecular material of similar velocity is associated with the arc filament system. The shocked molecular material receives the bulk of the frictional heating, that is \((1-k)/k\) times what the loop gets. Assuming the length of that part of the loop which is ramming into molecular material to be \( 10 \text{ pc}, \) the cross section \( 1 \text{ pc} \) and \( k = 0.1, \) we find a total heating of the ambient medium of \( 3.24 \times 10^{39} \text{ ergs s}^{-1} \) which will be essentially taken from the total loop magnetic and kinetic energy. This heat input is ultimately radiated through various molecular lines and dust emission.

VIII. CONCLUSIONS

We have developed a simple model for the production and propagation of magnetized loops in the Galactic center. Our central result is that a magnetized model can reproduce the filamentary, asymmetric structures on all scales from 100 pc to subparsec scales in the Galactic center. The idea that magnetic loops are being shed from some central active source, hidden inside less than 0.25 pc suggests that the Galactic center morphology arises from central "activity," as opposed to the complicated trajectories that tidally disrupted clouds on scales \( \gtrsim 1 \text{ pc} \) can take. The interaction of such loops with the 2–5 pc molecular torus, and the interaction with the GCL can explain their observed properties. A rather exotic but fully self-consistent prospect is that Sgr A itself be the closed magnetized corona of the 2–5 pc torus and consists of an assemblage of loops anchored to it. The known coronal heating processes suffice to keep this gas hot against radiative losses. If the large molecular line widths are due to shear motions, then the coronal loops strongly heat and radiate away this shear energy.

Our specific conclusions are as follows:

1. The radio and molecular gas morphology on all scales inside the Galactic center lobe (GCL) may be explained in terms of the expansion of strongly magnetized loops, similar in nature to solar coronal mass ejections, and their interaction with the 2–5 pc torus and 30–50 pc portion of the GCL.

2. The magnetic loops have a toroidal field which readily explains the braided appearance of the radio continuum emission on the 2 pc scale.

3. The barlike feature on the 2 pc radio continuum maps can be viewed as a piece of a magnetic loop with field strength \( \sim 10^{-2} \text{ G} \) which is colliding and reconnecting with the ionized inner edge of the 2 pc molecular torus. At all reconnection points such as the intersection with northern arm and western arc velocity gradients of order \( \pm 300 \text{ km s}^{-1} \) are expected, in accordance with the observations.

4. The loop-torus interaction feeds energetic particles and shear Alfvén waves into the torus, and deposits mass and energy. The mechanical energy input by expanding loops in the torus is a significant contribution to its energy balance. The Alfvén speed in the torus (60 km s\(^{-1}\)) is less than torus rotation (100 km s\(^{-1}\)), so disturbances are carried downstream from the reconnection points. This explains the radio morphology. The strong field prevents clumps in the torus from being destroyed by shear effects.

5. The Sgr A radio structure itself is a collection of trapped "coronal loops." These loops are heated by shear motions of order \( \sim 12 \text{ km s}^{-1} \), acting on their footpoints, embedded in the torus. The total luminosity that can be so converted to radiation is \( \sim 10^{37} \text{ erg s}^{-1} \).

6. Similar, but more powerful heating may be supplied in the corona of the source engine, which can account for the losses of the \( 1.5 \times 10^{-3} \text{ M}_\odot \text{ yr}^{-1} \) wind that the observed X-ray emitting gas imply, if connected to opened field lines.

7. Solutions for loop propagation through the hot interior of the GCL show that expanding loops, if unimpeded by the molecular torus, achieve peak velocity of \( \sim 300 \text{ km s}^{-1} \) at \( \sim 1 \text{ pc} \) scales and thereafter gradually decelerate under the action of the gravitational potential and retarding gas drag. At 30–60 pc, they have no more than 100 km s\(^{-1}\) velocities. If a massive hole is present (\( \sim 10^6 \text{ M}_\odot \)), the ratios of magnetic to gravitational energy densities in the loop is of order unity in order for these speeds to be achieved. Less strongly magnetized loops may achieve such speeds if the black hole mass is less massive (\( \lesssim 10^4 \text{ M}_\odot \)).

8. Bridge filaments at the 30 pc scale are portions of a magnetic loop, which has detached from Sgr A, and is colliding with the GCL. This collision produced a nonlinear wake of shear Alfvén surface waves on the rotating GCL. These waves damp and heat the GCL to 9000 K (\( n_e \sim 5–10 \text{ cm}^{-3} \)). The
magnetic field of the bridge filament is $B_{\text{bridge}} \sim 10^{-3}$ G. The magnetic energy density of the filament exceeds its gas pressure by 100.

9. Strong particle acceleration occurs at reconnection points where the merging loop (bridge) meets the GCL. Nonthermal emission arises by synchrotron radiation from electrons with Lorentz factors of order $10^4$. G. Alfvén waves which propagate up the GCL at $\approx 170$ km s$^{-1}$ and can also create particle acceleration.

10. The GCL radio emission is restricted to plumes on a cylindrical "shell." All emission is driven by the loop-GCL interaction.

11. The cool, magnetized GCL is Rayleigh-Taylor unstable with respect to the hot, poorly magnetized, interior to the radio-arc filaments.

12. The "threads" are portions of magnetic loops which have reconnected with the GCL and expanded out to $\sim 100$ pc. The GCL may contain a large number of them at a very low luminosity.

13. A central body must have a mass $10^{5} - 10^{6} M_{\odot}$ if sufficient magnetic flux is to be trapped so that bridge and thread structures can be produced. This need not be a compact body. In fact, less extreme conditions are required for loop propagation if a massive black hole is not present in the Galactic center.

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