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STRUCTURED CORONAE OF ACCRETION DISKS

A. A. GALEEV* AND R. ROSNER
Harvard-Smithsonian Center for Astrophysics
AND
G. S. VAIANA
Harvard-Smithsonian Center for Astrophysics; and
Istituto e Osservatorio Astronomico di Palermo, Italy
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ABSTRACT

A model for the fluctuating hard component of intense cosmic X-ray sources (such as Cyg X-1) is developed, based upon the amplification of magnetic fields by convective motions and differential rotation within a hot ($T \gtrsim 10^6$ K) accretion disk. Field reconnection within the inner portion of the disk is shown to be ineffective in limiting field amplification; magnetic fields may therefore attain strengths comparable to the equipartition value, leading to their emergence via buoyancy in the form of looplike structures and resulting in a very hot ($T > 10^8$ K) magnetically confined, structured corona analogous to the observed structure of the solar corona. The energy balance of these loop structures is examined, and it is shown that the disk soft X-ray luminosity determines the predominant energy loss mechanism in loops: at low disk luminosities, thermal bremsstrahlung from these loops dominates and contributes a steady, shot-noise–like hard X-ray component. At high disk luminosities the emerging loops are Compton-cooled; the soft X-ray flux from the disk is Comptonized by the emerged loops, forming a transient, flarelike hard X-ray component.

Subject headings: hydromagnetics — stars: accretion — stars: coronae — X-rays: binaries

I. INTRODUCTION

Observations of compact X-ray sources thought to be associated with close binary systems have led in the past decade to the development of theoretical models which account for the X-ray emission by invoking accretion of gas onto the compact, collapsed component (see Blumenthal and Tucker 1974). The most detailed observational and theoretical work has been done for the X-ray source Cyg X-1 (see Oda 1977; Eardley *et al.* 1978), and for this reason we shall focus upon this source in the following discussion. The basic observational results we shall address, whose details are to be found in the above-mentioned surveys, are as follows:

a) Both optical and X-ray observations show periodic variability characteristic of a binary system; in particular, the X-ray source has been identified with the spectroscopic binary HDE 226868.

b) The energy spectrum of X-ray emission shows evidence for the presence of two components. The hard ($E > 10$ keV) component is always present, whereas the soft ($E < 10$ keV) component has been reliably detected only during Cyg X-1's "high state." There is weak evidence that the intensity of the hard component is anticorrelated with the intensity of the soft component.

c) The X-ray emission is known to be highly variable, on time scales ranging over 10 orders of magnitude, down to fluctuations at the millisecond level. Monte Carlo simulation has shown much of the variability to be characteristic of that associated with shot noise.

The thrust of our discussion will be to develop a coherent model relating the two X-ray components and their temporal variability; as part of this development we suggest a reason why Cyg X-1 may be distinguished from other binary X-ray sources. We shall not dwell upon other proposed models for Cyg X-1 except where directly relevant to our discussion.

It is now thought that the observed hard X-ray component originates from a hot ($T_e \gtrsim 5 \times 10^8$ K), optically thin plasma near the compact soft X-ray source, the latter most likely an accretion disk surrounding a gravitationally collapsed object (cf. Eardley *et al.* 1978). A wide variety of specific models have been proposed to account for these observations; most recently it has been suggested that the hard component derives from "Comptonization" of soft X-rays in a uniform hot corona surrounding the cooler, soft X-ray emitting accretion disk (Liang and Price 1977, Bisnovatyi-Kogan and Blinnikov 1977). This suggestion, to some extent motivated by the fact that standard accretion disk models are convectively unstable (cf. Shakura and Sunyaev 1973), is based upon an analogy with the solar corona, which is conventionally thought to be fairly homogeneous, and

* On leave from the Space Research Institute, Moscow, USSR.

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1979ApJ...229..318G

13

Coronal Loops.

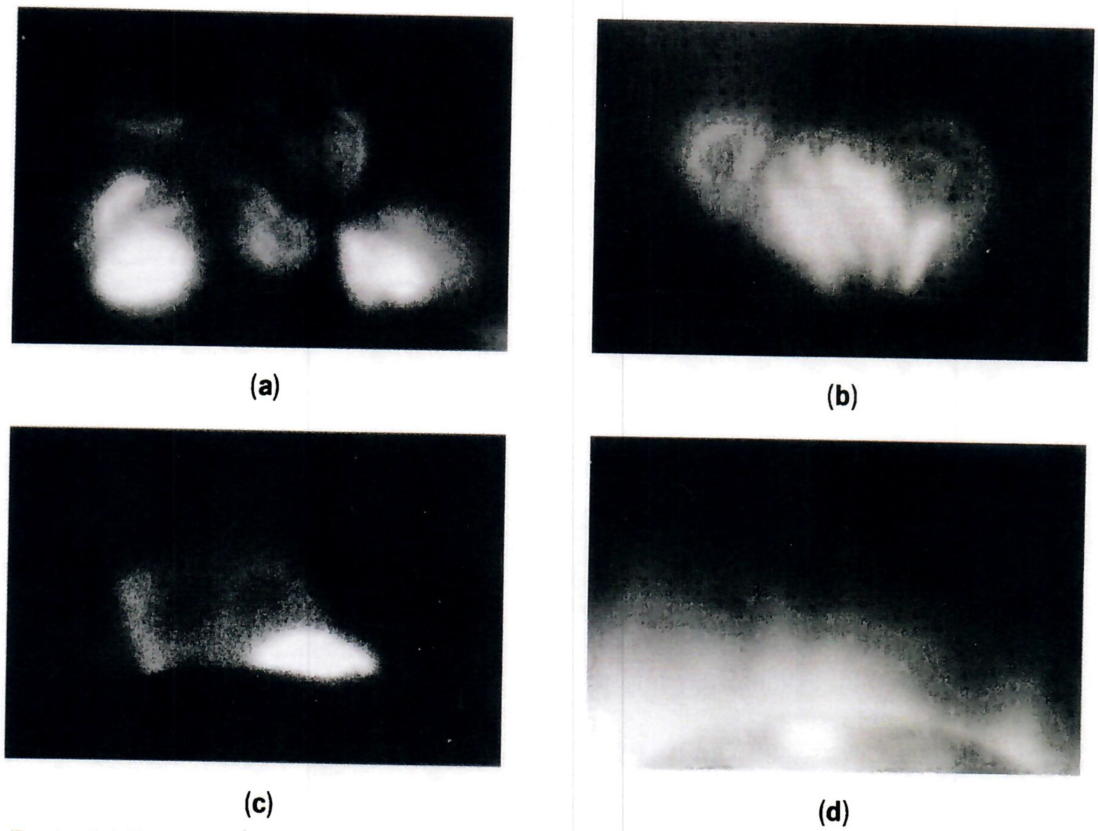

FIG. 1.—Soft (2–32, 44–54 Å) X-ray images of a variety of typical solar coronal regions obtained by the HCO/AS&E S-054 X-ray telescope on board *Skylab*: (*a*) emerging small active regions; (*b*) evolving large active region; (*c*) flare loop seen on solar limb; (*d*) large loop structures in "Quiet Sun." The X-ray emission derives primarily from closed, looplike structures defined by coronal magnetic fields which emerge from the solar convective zone. Although the plasma regime envisaged here for the accretion disk corona is vastly different from that of the Sun, its geometric structure is likely to be quite similar to that pictured because in both cases the low-β coronal plasma is dynamically controlled by magnetic fields whose footpoints are embedded in a convectively unstable, $\beta \sim 1$ plasma.

n.b. Much better modern pics exist

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1979ApJ...229..318G

180

heated by acoustic flux generated by turbulent convection motions in the outer solar envelope (cf. Athay 1976). In these models magnetic fields are invoked primarily to provide an efficient mechanism for angular momentum transfer within the accretion disk (Eardley and Lightman 1975) and are not involved directly in the maintenance of the hot corona.

This argument by analogy is, however, vitiated by recent EUV and X-ray observations of the solar corona, particularly by the instruments carried on board *Skylab*; these have shown the solar corona to be composed of a variety of complex loop structures generally associated with underlying photospheric and chromospheric magnetic field complexes, in contrast with the homogeneous geometry previously assumed. The bulk of solar X-ray emission derives instead from magnetically confined, looplike volumes; volumes which appear open to the interplanetary medium show relatively low X-ray brightness and correlate well with high-speed solar wind streams (Fig. 1). These observations suggest that spatial confinement is the key to obtaining a hot, dense corona (see Vaiana and Rosner 1978); in particular, it has been argued that the necessary element for the formation of a strong corona appears to be the presence of a confining magnetic field.

Magnetic fields have, of course, long been considered an important element in the dynamics of the accretion disk, primarily as a mechanism for supplying internal stresses required for efficient angular momentum transfer (Eardley and Lightman 1975, Ichimaru 1977). These calculations assume that the level of field fluctuations is primarily determined by dissipative processes *within* the disk itself. We shall show explicitly, however, that even under the most favorable conditions of field annihilation, internal dissipative processes are ineffective at limiting the growth of magnetic field fluctuations. This consideration leads us to reject these previous accretion disk models invoking relatively weak ($\beta \gg 1$) magnetic fields and suggests instead a new model in which the magnetic field plays a more central role. In this model strong magnetic fields ($\sim 10^8$ gauss) can be realistically generated within the inner portion of an accretion disk by the joint action of plasma thermal convection and differential rotation along Keplerian orbits. Field amplification will then be limited by nonlinear effects; as a consequence of buoyancy, magnetic flux will be expelled from the disk, leading to an accretion disk corona consisting of many magnetic loops where the energy is stored. The magnetic fields in these loops can provide an energy source for plasma heating, leading to a state in which the loops contain very hot, relatively low-density plasma as compared to the disk itself. Hard X-ray emission is the consequent result, due both to bremsstrahlung and to Comptonization of soft X-rays from the cooler underlying disk; which of these two loss processes dominates will be shown to be determined by the accretion disk luminosity, and both the luminosity and the time scale of fluctuations of the ensuing hard X-ray component are demonstrated to be consistent with observations.

II. MAGNETIC FIELD GENERATION AND THE FORMATION OF CORONAL LOOPS

Magnetic field generation due to differential motion of conductive media is usually described in the MHD limit with the aid of the induction equation for the magnetic field (cf. Parker 1955)

$$\frac{\partial \boldsymbol{B}}{\partial t} = \text{curl}\,[\boldsymbol{v} \times \boldsymbol{B}] + \frac{c^2}{4\pi\sigma}\nabla^2 \boldsymbol{B}\,, \qquad (1)$$

where $\boldsymbol{B}$ is the magnetic field induction, $\boldsymbol{v}$ the velocity of the fluid, and σ the electrical conductivity. For typical parameters of the plasma in the accretion disk (plasma density $n \approx 10^{22}\ \text{cm}^{-3}$, plasma temperature $T \sim 10^7$ K; cf. Bisnovatyi-Kogan and Blinnikov 1977) the magnetic Reynolds number Re_m is large,

$$\text{Re}_m \approx 10^{12}\,; \qquad (2)$$

therefore, magnetic field evolution via the plasma differential motion is well described by equation (1) if we neglect the (classical) collisional dissipation of the magnetic field implied by the last term on the right-hand side of equation (1). In the case of Keplerian differential rotation, equation (1) then describes (assuming an axisymmetric geometry) the amplification of the azimuthal magnetic field B_ϕ in the presence of a seed radial magnetic field B_r:

$$\frac{\partial B_\phi}{\partial t} = r\frac{\partial \Omega}{\partial r}\cdot B_r\,, \qquad (3)$$

where $\Omega = (GM/r^3)^{1/2}$ is the Keplerian angular velocity. It has been proposed that reconnection of the azimuthal magnetic field then accounts for the generation of the radial magnetic field and that the magnetic field stress

$$t_{\phi r} = (1/4\pi)B_\phi B_r \qquad (4)$$

provides the primary mechanism for angular momentum transfer within the accretion disk (Eardley and Lightman 1975). We now show that even the fastest (Petschek-type) reconnection mechanism is insufficiently rapid to develop effectively in the inner portion of the accretion disk and that the buildup of magnetic fields within the disk is instead limited by nonlinear effects related to convection.

To this purpose we consider the thermal convection of the highly conducting plasma within the accretion disk. Since convection takes place primarily perpendicular to the plane of the disk, we shall assume differential rotation to remain the dominant mechanism for azimuthal magnetic field (B_ϕ) generation; the generation of the remaining field components (B_r and B_z) will then be dominated by convection-mediated effects. For convection cells whose aspect ratio is $\sim O(1)$, the radial magnetic field spatial scale will then be of the order of the convective cell size z_0, equal to the half-thickness of the disk; in that case the right-hand side of equation (3) can be replaced by the

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1979ApJ...229..318G

where α is a small parameter relating the plasma stress $t_{\phi r}$ to the pressure p (e.g., $t_{\phi r} = \alpha p$), and where we have used the estimate of Bisnovatyi-Kogan and Blinnikov (1977) for the convection velocity $v[\approx \alpha^{1/3} c_s]$. Then using equations (6) and (8)–(10), we obtain the limiting strength of the magnetic field:

$$B_\phi^2/4\pi \approx \rho c_s^2 . \tag{11}$$

Thus, the magnetic field pressure becomes comparable to the ambient gas pressure, as one would expect from simple energy equipartition arguments; however, our conclusion cannot be based upon equipartition alone because the latter implicitly assumes that field reconnection does not come into play.

Our argument therefore requires an explicit comparison of the time scales associated with field growth and reconnection, and a demonstration that—for some significant portion of the accretion disk—no reconnection occurs which may stop magnetic field growth before the nonlinear limit is reached. In a plasma with $n \approx 10^{22}\ \mathrm{cm}^{-3}$, $T = 10^7$ K, $B \approx 7.5 \times 10^7$ gauss, $l \sim 3 \times 10^6$ cm, the Reynolds number is $\mathrm{Re_m} \approx 10^{12}$, and the upper limit for the Petschek-type reconnection time is (Priest and Soward 1976):

$$\tau_R^{-1} = \frac{\pi v_A l^{-1}}{4(\ln \mathrm{Re_m} + 0.74)} \approx 2.1 \times 10^{-2} \frac{v}{z_0} , \tag{12}$$

where $v_A = B/(4\pi\rho)^{1/2}$ is the Alfvén speed and is of the order of the sound speed (eq. [11]). Reconnection is therefore unimportant if $\tau_R/\tau_G > 1$, or (using eqs. [7] and [12])

$$r/z_0 \lesssim 140 . \tag{13}$$

Now, within the inner portion of the accretion disk $z_0 = 3r_0(L/L_c)[1 - (r_0/r)^{1/2}]$ (Bisnovatyi-Kogan and Blinnikov 1977); therefore, for $1.2r_0 \lesssim r \lesssim 10r_0$, we obtain

$$2.25 \lesssim (r/z_0)(L/L_c) \lesssim 5 , \tag{14}$$

where L/L_c is the luminosity in units of the Eddington limit $L_c = 4\pi c G M m_p/\sigma_T$. Comparing equations (13) and (14), we see that for $L \sim 0.1 L_c$—in the most radiative part of the disk ($r \approx 3r_0$)—equation (13) is easily satisfied and therefore reconnection is unable to suppress magnetic field generation. In that case the argument leading to equation (11) applies. Magnetic flux tubes with such strong magnetic field strengths will contain less plasma than their ambient surroundings in order to maintain pressure balance; therefore they are subject to buoyancy forces and will penetrate the accretion disk to form "coronal" loops. As soon as these field lines emerge from the disk, reconnection becomes faster because the coronal density is much lower. Reconnection can therefore provide an efficient mechanism for plasma heating in the emerged loops; this possibility is explored below (§§ III and IV). A sketch of the envisaged geometry is shown in Figure 3.

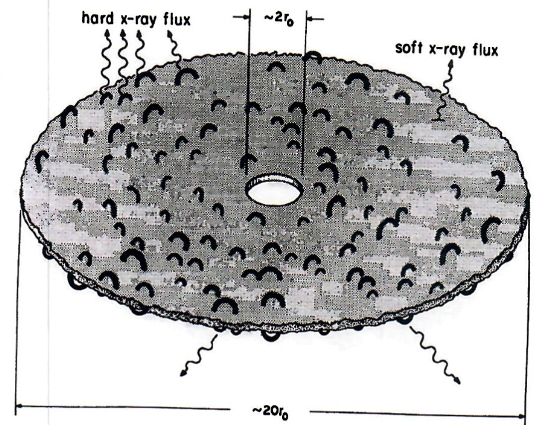

FIG. 3.—Schematic drawing of the inner accretion disk coronal geometry, with $r_0 \equiv 6GM/c^2 \sim 10^7$ cm in the case of Cyg X-1; only the inner portion of the disk is shown. The soft X-ray component derives from the relatively cool disk (including the outer portion not shown here) while the hard X-ray component is emitted by the ensemble of hot ($T_e \gtrsim 5 \times 10^8$ K) plasma loop structures which have emerged from the inner disk. The length of typical loop structures is of the order of 10^6 cm, but can be expected to vary considerably as the loops evolve and their magnetic fields decay.

III. PLASMA THERMAL BALANCE IN CORONAL LOOPS: LOW LUMINOSITY STATE OF THE ACCRETION DISK

We now consider the thermal balance of plasma entrained within the magnetic loops formed above the accretion disk (§ II). At the temperatures of interest ($\gtrsim 10^8$ K), and for the loop scale sizes involved ($\lesssim 10^6$ cm), typical dynamic relaxation times are less than 10^{-2} s; furthermore, the pressure scale height substantially exceeds the relevant physical dimensions. Therefore, on the time scale of ~ 1 s, we can reasonably expect quasi-stationary conditions, with $p \approx$ constant along the magnetic field. This precludes modeling of the impulsive phase of loop eruption from the accretion disk, during which the loop is filled with hot plasma. In the present case, thermal balance is governed by the energy conservation equation (Rosner, Tucker, and Vaiana 1978)

$$E_H - \frac{\partial}{\partial s} F - E_R = 0 , \tag{15}$$

where F is the thermal conduction flux, E_H is the heating rate, E_R is the relevant radiation rate (see below), and s is the coordinate along the field lines. We assume that Compton cooling (Illarionov and Sunyaev 1972; Felten and Rees 1972) of loops is relatively ineffective in the low-luminosity state; this assumption will be verified below.

For sufficiently hot plasma in the loop ($T \gtrsim 5 \times 10^8$ K), the stationary thermal flux is strongly inhibited by the ion-sound instability of the thermal flux (Forslund 1970); calculations of the thermal flux based upon a quasi-linear theory of the ion-sound instability

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NANOFLARES AND THE SOLAR X-RAY CORONA[1]

E. N. PARKER
Enrico Fermi Institute and Departments of Physics and Astronomy, University of Chicago
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ABSTRACT

Observations of the Sun with high time and spatial resolution in UV and X-rays show that the emission from small isolated magnetic bipoles is intermittent and impulsive, while the steadier emission from larger bipoles appears as the sum of many individual impulses. We refer to the basic unit of impulsive energy release as a *nanoflare*. The observations suggest, then, that the active X-ray corona of the Sun is to be understood as a swarm of nanoflares.

This interpretation suggests that the X-ray corona is created by the dissipation at the many tangential discontinuities arising spontaneously in the bipolar fields of the active regions of the Sun as a consequence of random continuous motion of the footpoints of the field in the photospheric convection. The quantitative characteristics of the process are inferred from the observed coronal heat input.

Subject headings: hydromagnetics — Sun: corona — Sun: flares

I. INTRODUCTION

The X-ray corona of the Sun is composed of tenuous wisps of hot gas enclosed in strong (10^2 G) bipolar magnetic fields. The high temperature ($2–3 \times 10^6$ K) of the gas is maintained by a heat input of about 10^7 ergs cm^{-2} s^{-1} (Withbroe and Noyes 1977), most of which is lost by radiation as EUV and X-rays. It is observed that the surface brightness of the active X-ray corona is essentially independent of the dimensions of the confining bipole (Rosner, Tucker, and Vaiana 1978) from the normal active region with a scale of 10^{10} cm down to the X-ray bright points at 10^9 cm, and in some cases even down to the small bipoles of 2×10^8 cm at the limit of resolution of present observational instruments.

The heat source that causes the X-ray corona has proved elusive. There is a direct equation between magnetic field strength and heat input (Rosner, Tucker, and Vaiana 1978; Golub *et al.* 1980), and given a source of heat of about 10^7 ergs cm^{-2} s^{-1} the formation of the corona is straightforward: The heated gas expands upward from the top of the chromosphere with a pressure scale height of $1–1.5 \times 10^{10}$ cm; the density of the rising gas increases to about 10^{10} atoms cm^{-3}, at which point radiative losses balance the heat input. The gas pressure is then 6–9 dyn cm^{-2}, the speed of sound is $2–3 \times 10^7$ cm s^{-1}, the magnetic pressure (10^2 G) is typically 4×10^2 dyn, and the Alfvén speed is 2×10^8 cm s^{-1}. The magnetic field is essentially force-free.

The traditional view has been that the convection below the visible surface of the Sun produces sound waves, gravitational waves, and magnetohydrodynamic waves which propagate upward into the overlying atmosphere where they dissipate and deposit their energy as heat in the ambient gas (Bierman 1946, 1948; Alfvén 1947; Schwarzschild 1948; Parker 1958; Whitaker 1963). More recently it has become clear that all but Alfvén waves are dissipated and/or refracted before reaching the corona (Osterbrock 1961; Stein and Leibacher 1974; Sturrock and Uchida 1981; Priest 1982). Presumably, then, it is primarily Alfvén waves that reach the active X-ray corona. The problem is that Alfvén waves are disinclined to dissipate in the corona. Indeed, it is just that disinclination that allows them to penetrate the chromosphere and transition region to reach the corona. Various ideas have been proposed to facilitate dissipation (cf. Hayvaerts and Priest 1983; Hollweg 1984, 1986, 1987; Kuperus, Ionson, and Spicer 1981; Ionson 1984; Lee and Roberts 1986; Davila 1987). The basic point is that in order to provide the necessary heat input without violating the observed upper limit of 25 km s^{-1} on the wave amplitudes (Cheng, Doschek, and Feldman 1979) the Alfvén wave must dissipate within about one period, which is reminiscent of the disintegration of a turbulent eddy (Hollweg 1984, 1986).

Alternatively it has been suggested (Parker 1979, 1983*d*, 1986*c*, 1988) that the X-ray corona is heated by dissipation at the many small current sheets forming in the bipolar magnetic regions as a consequence of the continuous shuffling and intermixing of the footpoints of the field in the photospheric convection. Insofar as the field is concentrated into separate individual magnetic fibrils at the photosphere, each individual fibril moves independently of its neighbors, producing tangential discontinuities (current sheets) between neighboring fibrils at higher levels where they expand against each other to fill the entire space (Glencross 1975, 1980; Parker 1981*a*, *b*; Sturrock and Uchida 1981). There is, however, a more basic effect, viz., a *continuous* mapping of the footpoints spontaneously produces tangential discontinuities (Syrovatsky 1971, 1981; Parker 1972, 1979, 1982, 1983*a*, *b*, *c*, *d*, 1986*a*, *b*, *c*, 1987*a*; Yu 1973; Tsinganos 1982; Tsinganos, Distler, and Rosner 1984; Moffatt 1985, 1986; Vainstein and Parker 1986). The discontinuities appear in the initially continuous field at the boundaries between local regions of different winding patterns. The tangential discontinuities (current sheets) become increasingly severe with the continuing winding and interweaving, eventually producing intense magnetic dissipation in association with magnetic reconnection (Parker 1983*d*, 1986*c*).

Now, fundamental to any theoretical idea on the energy input to the corona is the mechanical work done on the magnetic field by the photospheric convection. Thus, far, observations have failed to detect either the expected wave motion or the expected shuffling and intermixing of the footpoints. The principal observational difficulty is the continuing inability to resolve the individual magnetic fibrils [with diameters of about

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→ Miscellaneous Magnetics

⇒ "layered disk" – toward planets . . . .

– disks cool, as accretion progresses.
→ ionization ↓

recall need: $\gamma \rho_i > \Omega$ for magnetic coupling + MRI.

– Cooler disk → layered

i.e. neutral ⟹ uncoupled magnetically

– ionized surface layer – MRI and accretion can occur.

- dead zone → weak, no turbulence

→ planet formation ?

→ easier to sediment

i.e. planets (from planetesimals) → sedimentation + coagulation > turbulence will work against

\+ Jeans / Toomre instability

turbulence spreads from surface layer, may inhibit sedimentation

Surface layer → accretion, but effective ?

→ buoyancy ?

Dead zone → planet formation (?!)

How reconcile ?

N.B.: α in disk models → [very small near star

$\alpha \sim .01$ in outer region

→ Physics of accretion — especially beyond MRI — remains open.