# Gravitational Energy Contribution to Coronal Heating

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## ABSTRACT

It is the conventional view that gravitational energy makes a negligible contribution to the thermal energy input into the solar corona. In this paper, it is shown that a flux tube emerging into the corona from the subphotospheric regions increases the gravitational potential energy of the corona and that a significant fraction of this energy can be subsequently converted into coronal thermal energy. The total gravitational energy added to the corona by a flux tube may be comparable to the magnetic energy associated with the current in the loop. Explicit calculations are given using a simple analytic model.

## I. INTRODUCTION

It is generally believed that the energy released in solar flares and coronal heating is stored in the magnetic fields associated with currents in the solar corona. The recent Skylab obserevations have indeed shown the existence of large numbers of loop–like structures in the corona. It is believed that these loops carry the currents. A typical flare–causing loop has a major radius of $10^4 - 10^5 km$ and minor radius of $10^3 - 10^4 km$ , while large numbers of smaller loops also exist. If a loop of major radius $2 \times 10^4 km$ and minor radius $2 \times 10^3 km$ carries a current of $4 \times 10^{10} A$, then the total magnetic energy associated with the structure is approximately $4 \times 10^{29}$erg. Indeed, in solar flare events, an estimated $10^{28} - 10^{32}$erg of energy is released on the time scale of tens of minutes. For non–flaring coronal heating, the energy release rates may be significantly lower.

Conventional theories have attempted to dissipate the stored magnetic energy by essentially microscopic plasma processes with varying degrees of success. These include double lyaer formation (Alfven and Carlqvist, 1967), magnetic reconnection (Vasyliunas, 1975) and anomalous resistivity (DeJager and Svestka, 1961). In addition, for coronal heating, wave heating has been proposed (Osterbrock, 1961). For more detailed reviews of the previous models, see Svestka (1976), Sturrock (1980), Brown and smith (1980), Athay (1976) and Vaiana and Rosner (1978).

The fundamental question regarding the precise nature of the mechanisms responsible for converting the magnetic energy into other forms of energy for a wide range of time scales and energy output has not been answered adequately by these models. Recently, a unified model has been proposed to account for magnetic energy release in a wide spectrum of events (Xue and Chen, 1980). This model utilizes the fact that a toroidal plasma experiences an electromagnetic force ($\boldsymbol{J} \times \boldsymbol{B}$) in the major radially outward direction. It was shown that a critical current $I_{cr} \approx 10^{10} - 10^{11} A$ exists such that a loop with $I \gg I_{cr}$ can drive itself strongly supersonic under some conditions dissipating a large fraction of the magnetic energy through shock waves in tens of minutes. For $I < I_{cr}$, a loop expands subsonically, heating the coronal plasma at much slower rates. It was also shown that overall loop structure, including what is below the photosphere, is critically important in determining the evolution of a loop. Thus, this model has shown that a toroidal plasma possesses an efficient electromagnetic mechanism for converting magnetic energy into other forms of energy on a wide range of time scales.

At this point, it is of interest to consider how a toroidal current loop can come to exist in the corona. It is believed that these loops "float" up from the interior of the sun (Parker, 1955, 1975). Because a flux tube has a larger radius of curvature at this stage than that at a more evolved stage (Fig. 1), the electromagnetic force due to the toroidal effects is small (inversely proportional to the radius of curvature). If, however, the density inside the loop $n_{in}$ is less than the density outside, $n_{out}$, the the loop is buoyant and can rise until $n_{in} = n_{out}$.

The effects of the buoyant force are well known. It is also the conventional wisdom that gravitational energy makes an insiginficant contribution to the energy released in solar flares and coronal heating (Sturrock, 1980; Brown and Smith, 1980). It is the purpose of this paper to show that gravitational energy is an important source of energy for the overall input of thermal energy into the corona. We will describe the mechanism in some detail using a simple analytic model.

Recently, a numerical model for coronal heating that utilizes buoyant force has been proposed (Book, 1980). This model, however, seeks to dissipate the magnetic energy of a "magnetic bubble" rising under the buoyant force, and gravitational energy is not considered. Furthermore, a force-free ($\boldsymbol{J} \times \boldsymbol{B} = 0$) self-similar configuration is used. It will be seen that the force-free assumption is inconsistent with the geometry and that the model lacks the mechanism to dissipate the magnetic energy.

## II. GRAVITATIONAL ENERGY

### A. A Model Current

Consider a flux tube of minor radius $a$ and length $2R$ located at the base of the corona as shown in Fig. 1. We assume that the two ends are anchored in the photosphere and that the current loop is completed inside the sun. The flux tube carries a toroidal current density $J_t$ and a poloidal current density $J_p$. For the model current loop discussed in this paper, we adopt surface current desnities where $J_t$ and $J_p$ are both uniform over a surface layer of thickness $\Delta \ll a$. The use of a surface current model does not affect the results qualitatively. Then, inside the loop, one has

$$\begin{aligned} B_t &= \left(\frac{2I_p}{cR}\right), \\ B_p &= 0, \qquad r < a \\ p &= p_{in}, \end{aligned} \tag{1}$$

and outside the loop, one has

$$\begin{aligned} B_t &= 0, \\ B_p &= \left(\frac{2I_t}{ca}\right)\frac{a}{r}, \qquad r < a \\ p &= p_{out}, \end{aligned} \tag{2}$$

where $r$ is the minor radial coordinate and $p_{in}$ and $p_{out}$ are the pressure inside and outside the current loop, respectively. For a nearly straight cylinder or large aspect ratio $(R/a \gg 1)$ torus, $p_{in}$ and $p_{out}$ are essentially constant. The quantities $I_t$ and $I_p$ are the toroidal and poloidal currents defined by

$$I_t \equiv 2\pi a J_t \Delta$$

and

$$I_p \equiv 2\pi R J_p \Delta.$$

The local pressure balance for a nearly straight cylinder is given by

$$p_{in} + \frac{B_t^2(0)}{8\pi} = p_{out} + \frac{B_p^2(a)}{8\pi} \tag{3}$$

It is assumed in this equation that the pressure is nearly uniform around the minor circumference because the minor radius is typically much smaller than the pressure scale height $H = 1.2 \times 10^{10} cm$ of the lower corona. Another assumption is that the effects of the kinetic energy on the moving boundary is neglected. It will be seen that the buoyant force cannot drive the loop strongly supersonic and that the kinetic energy density of the corona as seen by the loop remains less than the magnetic energy density inside the current loop. As a first approximation, we neglect the kinetic energy effects.

At this point, we choose a particular configuration for detailed consideration. We choose

$$n_{out} > n_{in} \tag{4}$$

and

$$B_t \approx 2B_p. \tag{5}$$

Equation (5) implies that

$$p_{in} < p_{out}. \tag{6}$$

The inequality (4) means that the current loop is buoyant. Equation (5) states that the current loop is stable to the $m = 0$ mode (sausage instability) and the global $m = 1$ (kink) mode (Kadomtsev, 1966). The inequality (6) states that the loop is stable to the local pressure driven instabilities (Suydam, 1958). Thus, we are considering a buoyant and MHD stable current carrying plasma. A current loop not satisfying these conditions are unstable to these destructive instabilities so that they cannot maintain the observed geometry longer than the MHD time scale.

The coronal temperature is generally believed to be approximately $T \approx 2 \times 10^6 K$. The pressure scale height $H$ is given by

$$H = \frac{2kT}{m_i g} = 1.2 \times 10^{10} cm,$$

where $g = 2.7 \times 10^4 cm/sec^2$ is the gravitation acceleration at the base of the corona. For the constant termperature region, the coronal pressure is

$$p_{out} = P_0 \exp(-z/H), \tag{7}$$

where $z$ is the height of the current loop measured from the base of the corona so that $n_{out} = p_{out}/2kT$.

For the specific value of the coronal density at $z = 0$, we take $n_0 \approx 10^{12} cm^{-3}$ where $n_0 = n_{out}(z = 0)$. This value of the coronal density is necessary because of the requirement of equilibrium force-balance (Xue and Chen, 1980). In addition, the above $n_0$ is consistent with the uppper limit of estimated values (see, for example, Brown and Smith, 1980).

## B. Gravitational Energy

We consider the dynamic evolution of the MHD stable current loop described by Eqs. (4)-(6) in a decaying atmosphere [Eq. (7)]. For $n_{out} > n_{in}$, the gravitational force is radially upward and is given by

$$F_G = 2\pi a^2 R m_i g(n_{out} - n_{in}), \tag{8}$$

where $g = 2.7 \times 10^4 cm/sec^2$. This force accelerates the loop upwards until the drag force balances it. At this point, the terminal velocity $V_*$ is reached, where the drag force is given by

$$F_D = C_d(2aRV^2 n_{out} m_i), \tag{9}$$

and the terminal velocity is

$$V_* = \left[\frac{\pi a g(n_{out} - n_{in})}{c_d n_{out}}\right]^{\frac{1}{2}}, \tag{10}$$

where $C_d$ is the drag coefficient, which we will set equal to 0.5 for concreteness. It is clear from the above equation that the maximum terminal velocity $\overline{V}_*$ occurs for $n_{in} \ll n_{out}$so that

$$\overline{V}_* = \left(\frac{\pi a g}{C_d}\right)^{\frac{1}{2}}. \tag{11}$$

For $a = 2 \times 10^8 cm$ and $C_d = 0.5$, the maximum termina velocity is

$$V_* \approx 5.8 \times 10^6 cm/sec$$

The sound spped in the corona is

$$C_s = \sqrt{\gamma \frac{p}{\rho}} \approx 2 \times 10^7 cm/sec,$$

where $T \approx 2 \times 10^6 K$ has been used.

The above two expressions are independent of the coronal density. Thus, we concludes that buoyant force cannot drive a flux tube of minor radius $\approx 2 \times 10^8 cm$ supersonic in the corona and that no rapid heating results from the action of the buoyant force. On the other hand, there is work done on the coronal material through the drag force. If we calculate the rate at which energy is dissipated, we find

$$\begin{aligned}\frac{dW_H}{dt} &= F_D\overline{V}_* \\ &= C_d(2aRn_{out}m_i)\overline{V}_*^3\end{aligned} \tag{12}$$

where $\overline{V}_*$ is the maximum terminal velocity of a loop and $W_H$ is the heat energy deposited in a limited region at the boundary of the loop. For our example, we find

$$\frac{dW_H}{dt} \approx 1.3 \times 10^{26} erg/sec$$

This value is approximately one order of magnitude smaller than the magnetic energy dissipation rate obtained for a supersonic loop of a comparable size driven by the electromagnetic force described by Xue and Chen (1980). However, a supersonic loop dissipates a large fraction of its magnetic energy in hundreds of seconds while the slowly expanding loop considered in this paper can dissipate magentic energy on much longer time scales. Thus, it is necessary to consider the overall evolutionary behavior of a loop and determine the total amount of gravitational energy that is added to the corona as a net energy input. Before we proceed, it is of importance to consider where the gravitational energy is stored.

In order to answer this question, we start with the corona before the looop emerges from the photosphere. At this point, the corona has a certain total potential energy $\overline{W}$. As the flux tube emerges, it does work $W_0$ against the corona such that

$$W_0 \approx (2\pi a^2 R)p_0, \tag{13}$$

where $p_0$ is the coronal pressure at $z = 0$. The corona has gained potential energy $W_0$ because it has been pushed up by the merging loop. The corona gains the same amount of potential energy if it is pushed up uniformly at the base of the corona by a distance of $(2\pi a^2 R)/4\pi R^2$ with the loop material distributed uniformaly at the base of the corona. Clearly this configuration is not stable to convection if $n_{in} < n_{out}$. If there is a height $z_*$ where $n_{in} = n_{out}$, then the loop can, in the absence of other forces, rise to $z_*$. That is, the corona can relax to a more stable configuration, releasing the excess potential energy through the motion of the loop. The amount of potential energy released as the loop rises to the height $z_*$ is given by

$$W_G = \int_o^{z*} dz F_G, \tag{14}$$

where $F_G$ is given by Eq. (8). This is the potential enery that the coronal material at heights lower than $z_*$ gains when it is pushed up by the merging flux tube. As the loop rises to $z_*$, the energy is dissipated. The coronal material above the height $z_*$ retains the added potential enery after a new equilibrium is established. The ultimate source of the gravitational energy is, of course, derived from the solar interior. As far as the energy source in the corona is concerned, the process described above is a simple one as can be visualized by considering an air bubble at the bottom of a cup filled with water.

## C. Evolution of the Current Loop

The remaining task is to calculate the quantity $W_G$ [Eq. (14)] for our model current loop. As the loop rises, we assume that the minor radius expansion is adiabatic so that

$$p_{in}(z) = \bar{p}\left(\frac{a_0}{a}\right)^{10/3}, \tag{15}$$

where $\bar{p} = p_{in}(z = 0)$ and $a_0 = a(z = 0)$. For mathematical tractability, we have used $R \approx$ constant although the loop length increases from $\approx 2R$ to $\approx \pi R$. This assumption causes the density $n_{in}$ to decrease less slowly so that $z_*$ will be somewhat less than what it would be if the loop length were allowed to vary. Thus, our estimate for $W_G$ will be somewhat lower.

We assume infinite conductivity so that

$$B_t(z) \approx B_{t0}\left(\frac{a_0}{a}\right)^2 \tag{16}$$

and

$$L_T I_t \approx \text{constant},$$

where $L_T$ is the total inductance of the entire circuit (Fig. 1). For the purpose of the present model calculation, we take the length of the loop above the photosphere to be much less that that of the entire circuit. If we define

$L$ to be the inductance associated with the loop above the phtosphere (i.e., the magnetic flux enclosed by the loop above the photosphere divided by $I_t$), then

$$\epsilon \equiv \frac{L}{L_t} \ll 1.$$

The importance of this quantity $\epsilon$ has been emphasized by Xue and Chen (1980). As the loop length increases from $2R$ to $\pi R$, the change in $I_t$ is reduced by the factor $\epsilon \ll 1$. So, we set

$$I_t \approx \text{constant}, \tag{17}$$

for consideration of the loop in the low corona. Using Eqs. (3), (7), (15), (16), and (17), we obtain

$$\frac{da}{dz} = \frac{a}{H} \frac{p_{out}(z)}{(10/3)p_{in} + 4(B_t^2/8\pi) - 2(B_p^2/8\pi)} \tag{18}$$

and

$$\frac{z}{H} = ln\left[\frac{\overline{p}}{p_0}\left(\frac{a_0}{a}\right)^{10/3} + \frac{B_{t0}^2/8\pi}{p_0}\left(\frac{a_0}{a}\right)^4 - \frac{B_{p0}^2/8\pi}{p_0}\left(\frac{a_0}{a}\right)^2\right]^{-1}, \tag{19}$$

where

$$p_0 + \frac{B_{p0}^2}{8\pi} = \overline{p} + \frac{B_{t0}^2}{8\pi}$$

and $p_0 = p_{out}(z = 0)$ and $\overline{p} = p_{in}(z = 0)$. The adiabatic assumption also gives

$$n_{in}(z) = n_0\left(\frac{a_0}{a}\right)^2$$

and

$$T_{in}(z) = T_0\left(\frac{a_0}{a}\right)^{\frac{4}{3}}.$$

Equations (18) and (19) describe the evolution of the current loop being pushed up by buoyant force. Using Eqs. (8), (14), and (18), we find

$$W_G = (2\pi a_0^2 R n_0 m_i g H)\{2 + \frac{1}{2}\frac{\overline{p}}{p_0}\left[1 - 5\left(\frac{a_0}{a_*}\right)^{4/3}\right] \tag{20}$$

$$- 2\frac{B_{t0}^2/8\pi}{p_0}\left(\frac{a_0}{a_*}\right)^2 + 2\frac{B_{po}^2/8\pi}{p_o}\left[1 - ln\left(\frac{a_*}{a_0}\right)\right] - \frac{\overline{n}}{n_0}\frac{z_*}{H}\}$$

with

$$\frac{\overline{n}}{n_0} = \frac{T_a}{T_0} + \frac{B_{p0}^2/8\pi}{p_0} - \frac{B_{t0}/8\pi}{p_0} \tag{21}$$

where $T_a$ is the ambient coronal temperature and $T_0$ is the internal temperature at $z = 0$.

We now consider the magnetic force acting along the minor radius

$$F_B = \frac{\Delta}{2c}(J_p B_t - J_t B_p)(4\pi a R) \tag{22}$$

where $\Delta$ is the thickness of the current layer. This equation shows that if the minor radius expands, the toroidal component of the magnetic field $B_t$ does work while the poloidal component $B_p$ gains work. For a current loop with $p_{in} < p_{out}$ (so that it is an MHD stable configuration), we have

$$J_p B_t - J_t B_p > 0$$

Thus, there is net energy loss by the magnetic field. Equation (22) can be re–written as

$$F_B = 4\pi a R\left(\frac{B_t^2}{8\pi} - \frac{B_p^2}{8\pi}\right) \tag{23}$$

The total magnetic energy released as the minor radius expands from $a_0$ to $a_*$ is given by

$$W_B \equiv \int_{a_0}^{a_*} da F_B \tag{24}$$

$$= 2\pi a_0^2 R\left(\frac{B_{t0}^2}{8\pi}\right)(1 - \frac{a_0^2}{a_*^2})4\pi a_0^2 R\left(\frac{B_{p0}^2}{8\pi}\right)ln\left(\frac{a_*}{a_0}\right),$$

where $a_* = a(z_*)$ is determined using Eq. (19).

It is of interest to consider the rates at which the magnetic energy and the gravitational energy are released as the loop rises. Consider

$$\frac{dW_G}{dt} = 2\pi a^2 R m_i g(n_{out} - n_{in})\left(\frac{dz}{dt}\right), \tag{25}$$

and

$$\frac{dW_B}{dt} = 4\pi a R\left(\frac{B_t^2}{8\pi} - \frac{B_p^2}{8\pi}\right)\left(\frac{da}{dz}\right)\left(\frac{dz}{dt}\right). \tag{26}$$

Using Eqs. (18) and (19), we find

$$\frac{dW_G}{dt} = 4aRC_d\frac{\overline{V}_*^2}{C_S^2}\left\{\frac{1}{2}\gamma\left(\frac{B_t^2}{8\pi} - \frac{B_p^2}{8\pi}\right) - \frac{1}{2}\rho_0 C_S^2\left(\frac{\overline{n}}{n_0}\right)\left[\left(\frac{a_0}{a}\right)^2 - \frac{T_0}{T_a}\left(\frac{a_0}{a}\right)^{10/3}\right]\right\}\left(\frac{dz}{dt}\right) \tag{27}$$

where $C_d$ is the drag coefficient, $\overline{V}_*$ is the maximum terminal velocity in the corona [Eq. (11)], $C_S$ is the sound speed in the corona, $\rho_0$ is the coronal mass density, $T_0 = T_{in}(z = 0)$ and $T_a$ is the coronal temperature $(2 - 3 \times 10^6 K)$. The second term in the curly brackets is typically one tenth of the first term if $\overline{n}/n_0 \approx 0.1$ initially. Then

$$\frac{dW_G}{dt} \approx 2aRC_d\gamma\left(\frac{\overline{V}_*}{C_S}\right)^2\left(\frac{B_t^2}{8\pi} - \frac{B_p^2}{8\pi}\right)\frac{dz}{dt}. \tag{28}$$

Equation (18) shows that

$$\frac{da}{dz} < \frac{a}{2H}$$

for any configuration satisfying local pressure balance. Thus, comparing Eqs. (25) and (27), we conclude that

$$\frac{dW_G}{dt} \approx \frac{dW_B}{dt}. \tag{29}$$

In fact, in the above example, the rate of gravitational energy release is greater than the magnetic energy release rate. That is, $dW_G/dt$ may be slightly larger (50%) than $dW_B/dt$ at the base of the corona. Note that the above statement applies to the region near the base of the corona because as the loop becomes more toroidal, the radially outward electromagnetic force begins to dominate. At this stage, the release of the magnetic energy due to major radius expansion dominates. The buoyant force converts a fraction of the gravitational energy into thermal energy while the resulting minor radius expansion gives rise to dissipation of magnetic energy. This process is much slower than the magnetic energy conversion due to major radius expansion.

It is important to note that the above analysis applies to a nearly straight cylinder. For a more realistic current loop, the entire volume does not rise so that the total amount of released gravitational energy is reduced from that calculated above by perhaps as much as a factor of 2. A more important effect of the toroidal geometry manifests itself in the magnetic enegy released. The minor radius expansion causes the toroidal magnetic field $B_t$ to lose energy ($J_pB_t$) and the poloidal field $B_p$ to gain energy ($-J_tB_p$) as shown by Eq. (25). In a toroidal geometry, exactly the opposite is true (Xue and Chen, 1980).

When a toroidal current–carrying plasma expands along the major radius due to its own self–fields, the rate $\delta\epsilon_t$ at which the toroidal magnetic field $B_t$ gains energy is

$$\delta\epsilon_t = \frac{\pi I_t^2}{2c^2}(\beta_p - 1)\delta z$$

and the rate at which the poloidal magnetic field $B_p$ loses energy is

$$\delta\epsilon_p = \frac{\pi I_t^2}{c^2}\left[ln\left(\frac{8R}{a}\right) - 1\right]\delta z.$$

where $R$ is the major radius so that $\delta z = \delta R$ for a semi-circle. The quantity $\beta_p$ is defined by

$$\beta_p = \frac{\overline{p} - p_{out}}{B_p^2(a)/8\pi} = 1 - \frac{B_t^2}{B_p^2},$$

and has the value

$$\beta_p \approx -2.88$$

for a quasi-equilibrium loop with $R/a = 10$. Note that $\delta\epsilon_p > 0$ and $\delta\epsilon_t < 0$ and that $|\delta\epsilon_p| > |\delta\epsilon_t|$. Therefore, there is a net loss of magnetic energy from $B_p$. As the loop rises, the minor radius expands so that magnetic energy is also lost. If we denote this value by $\delta\epsilon$, then

$$\delta\epsilon = |\beta_p|\frac{\pi I_t^2}{c^2}\left(\frac{R}{a}\frac{da}{dR}\right)\delta z.$$

Defining $\delta\epsilon_T == \delta\epsilon_t + \delta\epsilon_p$, w we have

$$\frac{\delta\epsilon_T}{\delta\epsilon} = 4.17.$$

Thus, the minor radius expansion contributes a small fraction of the magnetic energy released. More importantly, there is a net grain of energy by the toroidal magnetic field component $B_t$. Thus, the magnetic energy release rate calculated in Eq. (25) is not relevant once the loop becomes toroidal. The toroidal effect, however, affects the gravitational energy only to the extent described above (i.e., about a factor of 2).

It is, thus, of interest to compare the magnetic energy release with gravitational energy release. It has already been shown that the gravitational energy conversion rate cannot be explosive. Thus, we compute the total energy released assuming an initial density differential of

$$\frac{n_0}{\overline{n}} = 5$$

where $n_0 = n_{out}(z = 0)$ and $\overline{n} = n_{in}(z = 0)$. In this rough comparison, we neglect the toroidal effect for the gravitational energy. Assuming $T_{in} \approx \frac{1}{2} T_{out}$ initially for illustration purpose, we find

$$\frac{z_*}{H} \approx 2.4$$

and

$$\frac{a_*}{a_0} \approx 1.49$$

then

$$\frac{\overline{p}}{p_0} = 0.1.$$

Using Eqs. (13) and (20), we see that

$$\frac{W_G}{W_0} = 2 + \frac{1}{2}\frac{\overline{p}}{p_0}\left[1 - 5\left(\frac{a_0}{a_*}\right)^{4/3}\right] - 2\frac{B_{t0}^2/8\pi}{p_o}\left(\frac{a_0}{a_*}\right)^2$$
$$+ 2\frac{B_{t0}^2/8\pi}{p_0}\left[1 - ln\left(\frac{a_*}{a_0}\right)\right] - \frac{\overline{n}}{n_0}\frac{z_*}{H},$$

where use has been made of $H = 2kT/m_i g$. For the above numerical example, we have

$$\frac{W_G}{W_0} \approx 0.77,$$

where

$$W_0 = 1.0 \times 10^{29} \text{erg}.$$

This shows that if the loop can rise to the height $z_*$ where $n_{in} = n_{out}$ (the natural termination point of the buoyant force), then a large fraction of the gravitational energy stored in the corona can be converted into thermal energy. It is important to note that there is a net grain of thermal enegy by the corona and that this energy is derived from the gravitational energy the corona gains as the curretn loop emerges in to the corona [Eq. (13)]. Comparing this energy with the magnetic energy associated with the current loop, we find the stored gravitational energy is comparable to the magnetic energy. Thus, we conclude that the gravitational energy is an equally important source of the coronal thermal energy as the magnetic field.

## III. SUMMARY AND DISCUSSION

In the preceding sections, it has been shown that the corona gains gravitational potential energy $W_0$ [Eq. (13)] when a flux tube emerges into the corona from the subphotospheric regions, and that if the flux tube is buoyant, then a significant fraction of $W_0$ is converted into thermal energy through drag as the flux tube "floats" up. Thus, there is a net thermal energy input to the corona in the process of forming the observed loops. It is important to keep in mind that this thermal energy is stored in all the coronal gas at heights $z < z_*$ [Eq. (14)] rather than in the loop itself. Thus, the conventional argument that gravitational energy is negligible as a source of thermal energy because of its low energy density in the vicinity of the loop is incorrect. Using a simple analytic model, the amount of gravitational energy converted into coronal thermal energy is shown to be comparable to the magnetic energy associated with the current. Although the gravitational energy cannot be released explosively as in flares, there are many more non-explosive coronal loops. Thus, it is suggested that the gravitational energy gained by the corona as a result of the emerging flux tubes is an important source of thermal energy for coronal heating.

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## FIGURE CAPTIONS

Fig. 1. Flux tube ("current loop") at the base of the corona. The length is $2R$ and the minor radius is $a$. The flux tube carries a toroidal current $I_t$ and poloidal current $I_p$.

Fig. 2. Plot of $z/h$ vs. $a/a_0$ as the flux tube rises.

Fig. 3. The intersections of $y = z/H$ and $y = ln[(n_0/\overline{n})a^2/a_0^2]$ for $n_0/\overline{n} = 2.5$, and $10$. The intersections in conjunction with Fig. 2 give $z_*/H$ and $a_*/a_0$.

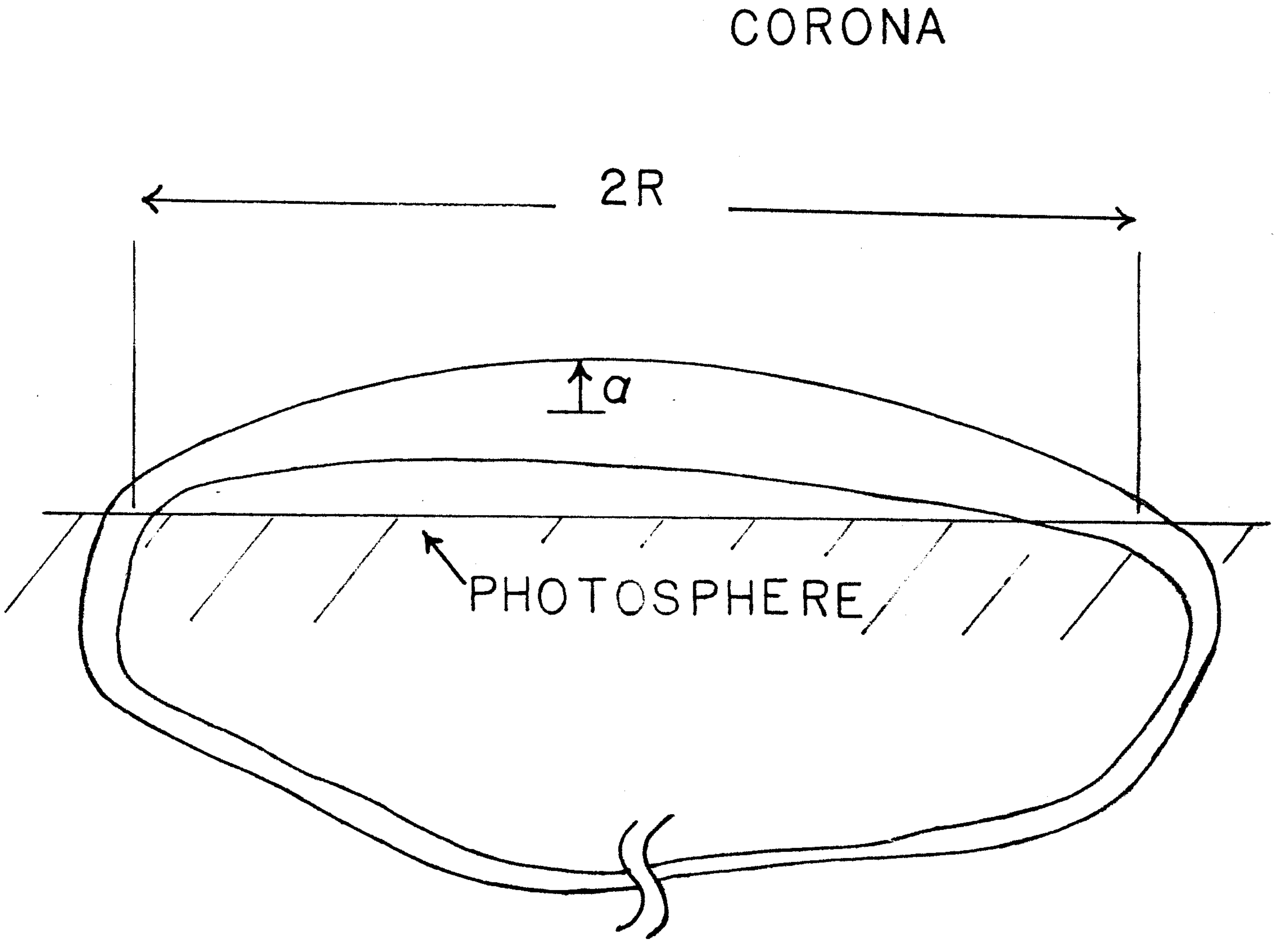


Fig. 1

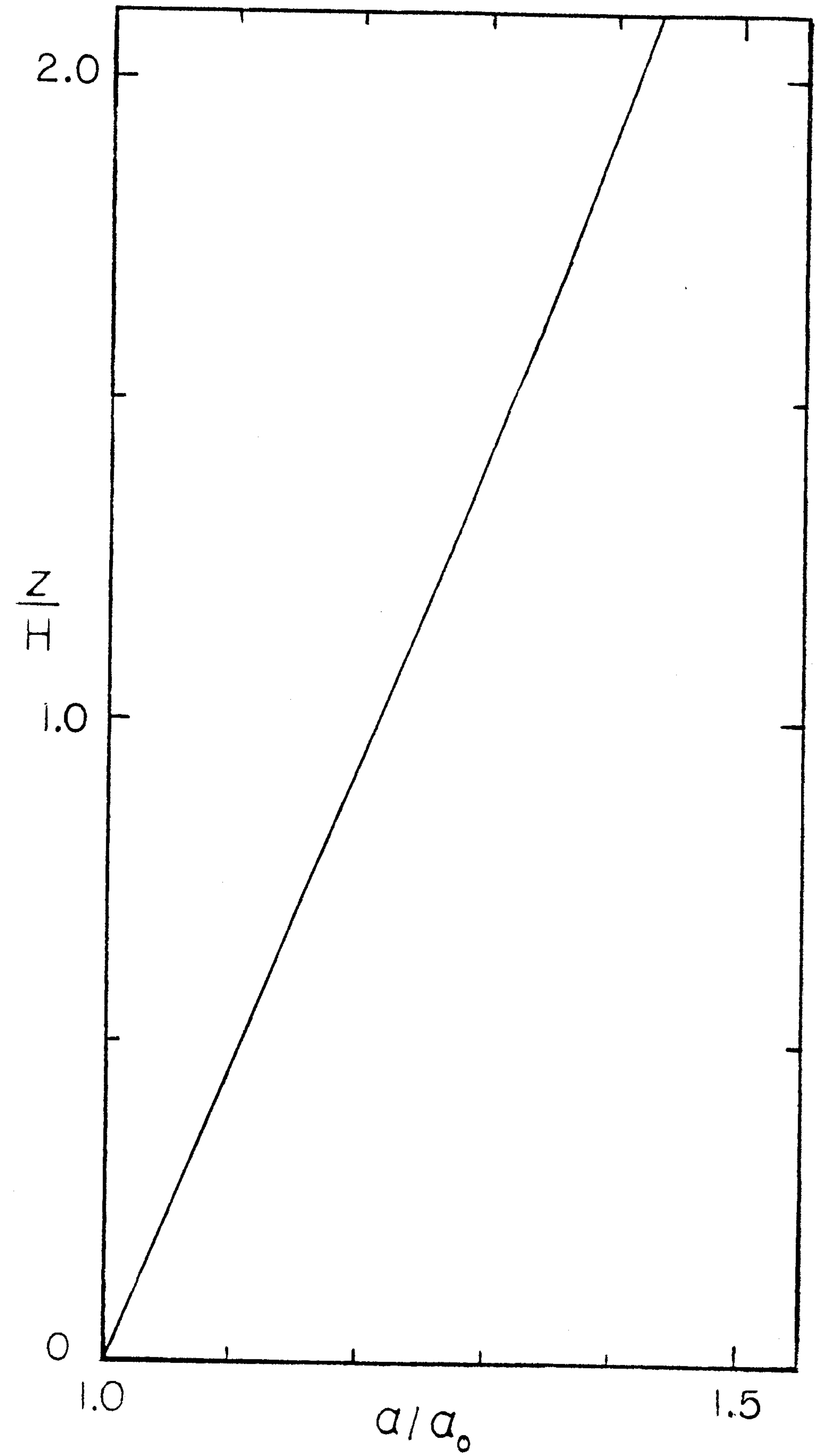


Fig. ?

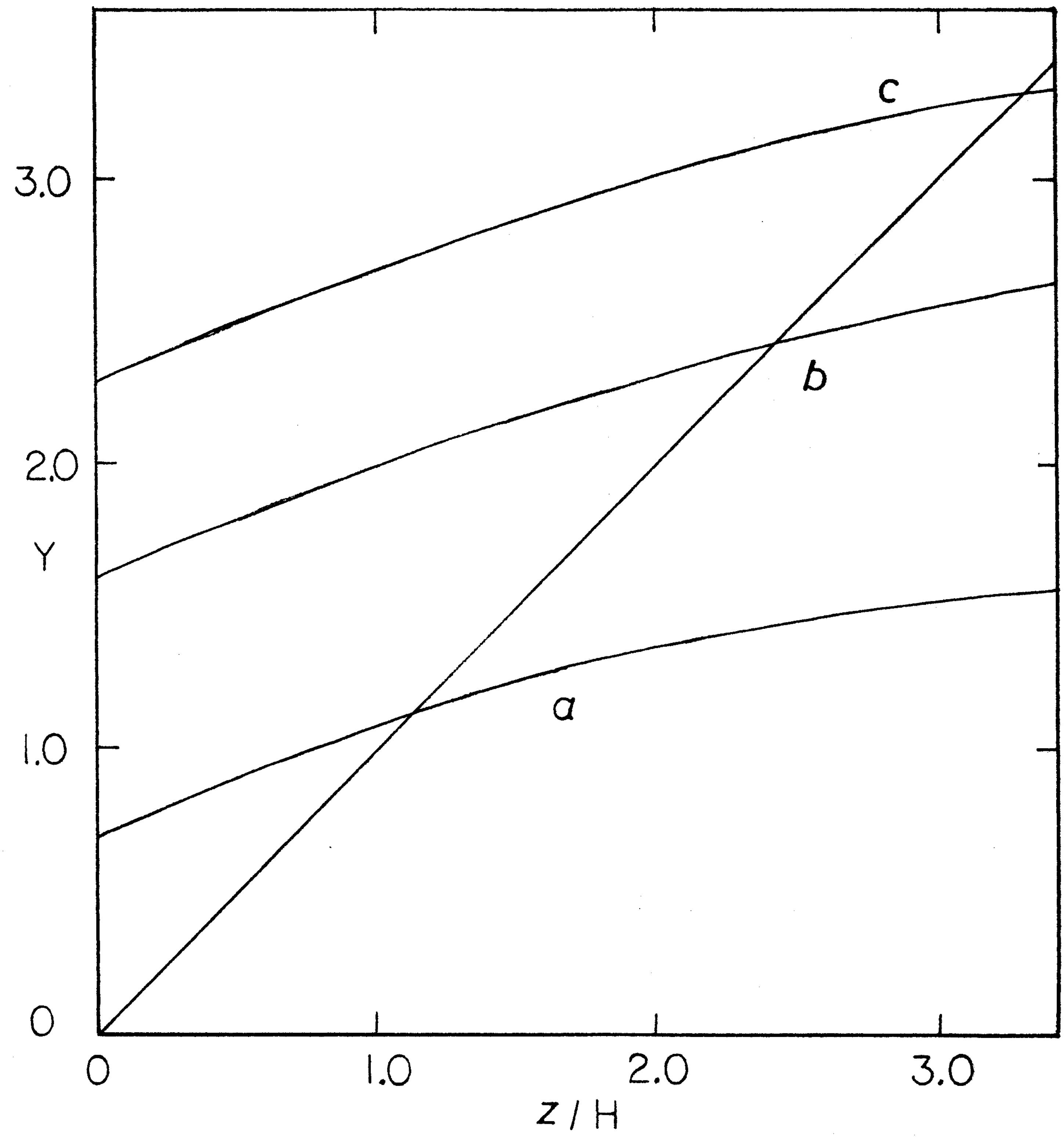


Fig. 3