Energy Dissipation and Temperature Anomaly in the Solar Corona

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Abstract

By introducing a new mechanism based on gravitational friction, we derive temperature estimates for the corona and provide a new perspective on the coronal heating problem. The study suggests that photon energy dissipation due to dissipative effects contributes significantly to the anomalously high temperatures in the solar corona.

1 Introduction

The solar corona exhibits temperatures ranging from 1 million to 8 million Kelvin, far exceeding the temperature of the photosphere, which is only about 6000 K. This stark discrepancy has been referred to as the *coronal heating problem*[1]. While a variety of models have been proposed to explain the source of this extreme heating, including energy transfer via magnetohydrodynamic (MHD) waves, a comprehensive understanding of this phenomenon remains elusive, despite decades of observational and theoretical efforts —more on this in section 3.

Observations indicate that the solar corona is not completely transparent for the non-scattered solar radiation. In addition to the heating problem, the spectral lines of light from the Sun are observed to shift as one moves from the center of the solar disk to the limb. This phenomenon of observed wavelength shift also called the *solar limb effect*, has suggested energy loss of radiations in the solar atmosphere. However, conventional explanations for these shifts, such as Doppler and Compton scattering, do not fully account for the observed data—more on this in section 2.

Understanding the physical processes responsible for both the energy loss of radiation and the heating of the corona could help address fundamental questions about the energy transfer mechanisms within the Sun's atmosphere. This paper aims to explore these phenomena through the framework of *gravitational friction*[2], a dissipative mechanism of energy loss, offering a potential unified explanation for both the coronal heating problem and the energy dissipation.

2 Energy Dissipation of Radiation

A differential shift in spectral lines was observed as one moves from the center of the solar disk to its limb, a phenomenon first identified by Halm in 1907[3]. He observed a shift of approximately 12 mÅ in the iron lines near the solar limb. Subsequent studies by Fabry and Buisson (1910) and Adams (1910)[4] expanded upon these findings, identifying similar shifts in hundreds of Fraunhofer lines across the visible spectrum. These shifts suggest that photons traveling through the solar atmosphere experience a change in wavelength, which is most prominent near the solar limb. Fundamentally, such redshift can be associated with some energy dissipation mechanism.

Traditionally, the solar limb effect has been attributed to two primary mechanisms: solar rotation and limb darkening. Due to solar rotation, the portion of the Sun moving toward the observer exhibits a blue shift, while the region moving away is red-shifted. However, the observed solar limb effect is characterized predominantly by a redshift across the entire limb, without a corresponding blue shift. This indicates that solar rotation alone cannot account for the full extent of the limb redshift.

The limb darkening is the phenomenon where the Sun appears dimmer at the edges compared to its center. It arises because light from the solar limb is emitted from higher, cooler layers of the atmosphere, in contrast to the deeper, hotter layers at the disk center. Thus, this is primarily an intensity-based effect, impacting the brightness and visibility of spectral lines. It does not directly influence wavelength shifts.

Additionally, atmospheric scattering mechanisms, such as Compton scattering, have also been proposed as possible explanations for the redshift of solar spectral lines. However, the predicted redshifts from Compton scattering alone are insufficient to explain the magnitude of the observed shifts[5].

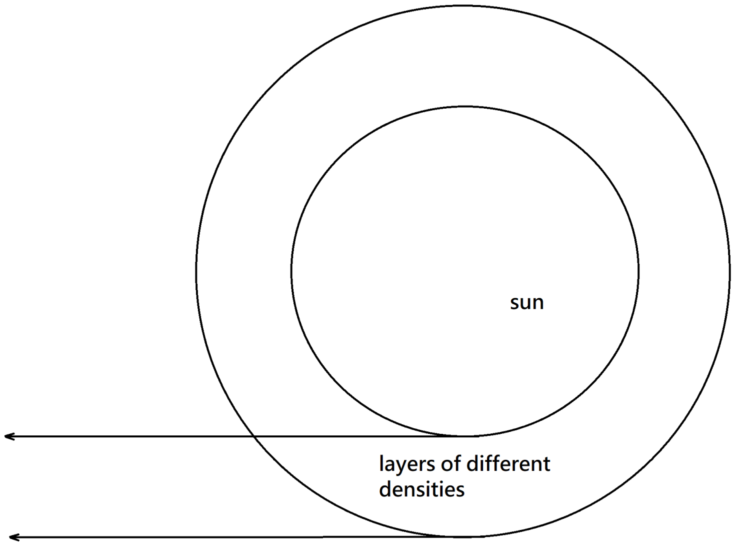

Figure 1: Illustration of the solar limb effect and the observed redshift of Fraunhofer lines.

More recent[6] studies have investigated the role of the solar atmosphere's density gradients in causing these redshifts. The solar atmosphere is a complex environment where photons can lose energy due to interactions with electrons and ions, leading to observed spectral shifts. It is important to note that we are not referring to the usual energy loss due to scattering processes. This suggests that non-scattering energy loss mechanisms beyond Doppler and Compton scattering may be at play, particularly for non-scattered photons.

3 Temperature Anomaly in the Solar Corona

Despite the fact that the corona is farther from the Sun's energy-generating core than the photosphere, it is vastly hotter. In an attempt to resolve this temperature anomaly, several mechanisms have been proposed to explain the transfer of energy from the Sun's surface to its outer layers, where it can heat the corona to such high temperatures. One of the most widely studied mechanisms involves the propagation and dissipation of *Alfven waves*, which are MHD waves that travel along magnetic field lines from the solar surface into the corona[7, 8]. These waves carry energy from the lower layers of the Sun and deposit it into the corona as they dissipate, potentially heating the surrounding plasma. However, numerical models of Alfven wave dissipation indicate that while they can contribute to heating, they are unlikely to provide the full explanation for the extreme temperatures observed in the corona[1, 8].

Another significant proposed mechanism for coronal heating is *magnetic reconnection*, where oppositely directed magnetic fields are forced together, breaking and reconnecting in new configurations. This process releases large amounts of energy, which could heat the coronal plasma. While magnetic reconnection events, such as solar flares and coronal mass ejections, are known to release vast amounts of energy, they are generally localized and sporadic, making it unclear whether this process alone can account for the steady heating observed throughout the corona[1, 7].

From the discussion in section 2, it is clear that the mechanism of energy loss for nonscattered radiations offers a compelling explanation for the observed redshift in the solar limb. Under gravitational interaction with the plasma density gradients, these non-scattered radiations can also potentially explain the temperature anomaly in the solar corona and the solar limb effect.

The gravitational interactions present a promising framework for explaining the redshift of non-scattered photons. Gravitational redshift, as introduced by Einstein, provides the foundational theory for how light loses energy as it escapes a gravitational field. In stellar environments like the Sun, photons experience gravitational redshift due to the Sun's gravitational pull, which causes a shift toward longer wavelengths without any scattering events. This energy loss, however, becomes more significant when considering additional factors such as the curvature of spacetime and interactions with surrounding plasma.

Lopresto et al. (1991) confirmed the gravitational redshift in the solar atmosphere through the observation of the solar gravitational redshift using the infrared oxygen triplet [9]. This study not only validated Einstein's predictions but also demonstrated that photons lose energy as they traverse the Sun's gravitational field, contributing to the observed shifts in the solar spectrum. However, this redshift due to gravitational fields alone does not fully explain the complexities of the solar limb effect.

To extend the gravitational framework further, recent theoretical work, including that of Ortiz et. al (2023), introduces the concept of gravitational friction as a mechanism for photon energy loss in stellar atmospheres [2]. Gravitational friction differs from traditional gravitational redshift in that it considers the continuous interaction between photons and the curved spacetime of a stellar atmosphere. While gravitational redshift occurs as photons climb out of a gravitational well, gravitational friction accounts for the energy loss as photons interact with the gravitational field and plasma environments along their path.

The gravitational friction mechanism is classified as non-scattering due to the nature of its dissipative interaction with the plasma density gradients. As photons traverse the increasingly diffuse plasma layers, their energy is gradually diminished through continuous interactions with the medium. Unlike traditional scattering processes, which involve discrete deflections and redistribution of the photon's momentum, this energy loss occurs without altering the photon's trajectory.

While gravitational redshift alone accounts for some observed shifts, the introduction of gravitational friction as a continuous energy dissipation process offers a more comprehensive explanation for the redshift of non-scattered photons observed at the solar limb.

As photons lose energy through gravitational friction due to the solar atmosphere, this energy is transferred to the surrounding plasma, increasing its temperature. This process would be particularly effective in the lower corona, where the density of the plasma is higher, and the gravitational effects are stronger. The dissipation of photon energy in this region could account for a significant portion of the heating observed in the corona.

Furthermore, the high temperatures of the corona may also be sustained by a combination of wave heating, magnetic reconnection, and gravitational photon energy loss. This multifaceted approach to the coronal heating problem provides a more complete picture of the physical processes at work in the Sun's outer atmosphere. The inclusion of gravitational frictional effects bridges the gap between observations of the solar limb effect and the unexplained heating of the corona, offering a unified framework for understanding these two longstanding issues in solar physics.

4 Redshift due to Energy Loss

In this section, we define the redshift of photons in the corona by using a gravitational friction model[2].

Zwicky (1929) proposed that redshift could arise due to energy loss mechanisms in interstellar space, going beyond the traditional Doppler effect explanation [5]. The redshift $1+z$ is related to energy loss by:

$$1+z=\sqrt{\frac{E_i}{E_f}},$$

which leads to the definitions in terms of frequency and wavelength:

$$1+z=\frac{\nu_i}{\nu_f}=\frac{\lambda_f}{\lambda_i}.$$

For gravitational friction, the initial photon energy is $E_i = pc$, and the final energy is:

$$E_f = pc - \frac{1}{3}G\pi m\rho r^2.$$

This gives the redshift:

$$1 + z = \sqrt{\frac{pc}{pc - \frac{1}{3}G\pi m\rho r^2}}.$$

Also we know that when $|x| < 1$, the following expansion formula applies:

$$(1 - x)^{-\frac{1}{2}} = 1 + \frac{1}{2}x + \frac{3}{8}x^2 + \frac{5}{16}x^3 + ... \tag{1}$$

Approximating for $G\pi\rho r^2 \ll 1$, by neglecting the quadratic terms and higher,we get: RK We can get rid of the square root and write $\frac{1}{2}$ in the denominator instead

$$1 + z = 1 + \sqrt{\frac{1}{3c_s^2}G\pi\rho r^2}.$$

Relating the gravitational redshift to wavelength, we find:

$$\frac{\lambda_f}{\lambda_i} = 1 + \sqrt{\frac{1}{3c_s^2}G\pi\rho r^2},$$

or equivalently:

$$\lambda_f = \lambda_i \left(1 + \sqrt{\frac{1}{3c_s^2}G\pi\rho r^2}\right).$$

Thus, the increase in wavelength (redshift) as photons travel through the corona contributes to the loss of photon energy, which in turn can be absorbed by the surrounding plasma, leading to the observed temperature rise in the corona. This effect, coupled with the photon energy loss mechanism described in the next section, provides a potential solution to the coronal heating problem.

5 Energy Transport Mechanism

The corona's energy transport mechanisms can be modeled by examining the adiabatic processes within the solar atmosphere. For an adiabatic process, the following relationships hold:

$$PV^\gamma = \text{constant}, \quad TV^{\gamma-1} = \text{constant},$$

or,

$$\frac{T}{P} = \frac{constant}{P^{\frac{1}{\gamma}}} = \frac{A}{P^{\frac{1}{\gamma}}}$$

where P is pressure, V is volume, T is temperature, and γ is the adiabatic index given by $\gamma = \frac{c_p}{c_v}$ where c_v and c_p are the specific heat capacities at constant volume and constant pressure, respectively.

Differentiating the above equation gives:

$$dT = A\left(1 - \frac{1}{\gamma}\right)\frac{1}{P^{\frac{1}{\gamma}}}dP$$

Using the previous equation, this can be rewritten as:

$$dT = \left(1 - \frac{c_v}{c_p}\right)\frac{T}{P}dP,$$

5.1 Energy Density

The energy density due to radiation pressure is:

$$P = \frac{1}{3}aT^4,$$

where a is the radiation constant [10]. From this, we can derive the expression for energy density E: We also know that:

$$dE = \frac{3}{2}dP$$

where dE is the differential of energy density [11]. After substituting from the previous equation, we obtain:

$$dE = \frac{3}{2}\frac{P}{T}\left(1 - \frac{c_v}{c_p}\right)^{-1} dT \tag{2}$$

Substituting the value of P we get:

$$dE = \frac{1}{2}aT^3\left(1 - \frac{c_v}{c_p}\right)^{-1} dT$$

$$2E = a\left(1 - \frac{c_v}{c_p}\right)^{-1} \int_{T_0}^{T_E} T^3 dT \tag{3}$$

Integrating this gives:

$$8E\left(1 - \frac{c_v}{c_p}\right) = a\left(T_E^4 - T_0^4\right)$$

which implies:

$$T_E^4 = \frac{8E}{a}\left(1 - \frac{c_v}{c_p}\right) + T_0^4$$

where $a = \frac{4\sigma}{c} = 3.024 \times 10^{-15}$ [12], which allows us to estimate the temperature at the outer layers of the corona.

6 Energy Loss Mechanism

Building on the work of *Carlos Ortiz (2020)* [13], the work done per unit volume against the surface tension energy along distance r is given by:

$$W_S = \Delta E = \frac{8\pi^2}{3}G\rho r^2$$

The redshift is given by:

$$z = \frac{\Delta E}{E} = \frac{\Delta\lambda}{\lambda}$$

Using equations above:

$$E = \frac{\Delta E}{z} = \frac{8\pi^2}{3}G\rho r^2\frac{1}{z}$$

So, the total work done against the gravitational friction from the photosphere to the outer corona is given by multiplying the above equation by the total volume. In equation 9), the E stands for the energy density for any unit shell. And T_E stands for the outward shell temperature. Therefore, to find the temperature at the outer corona, we replace the energy density by total energy by multiplying it with the total volume. Therefore,

$$E = \frac{8\pi^2}{3} G\rho r^2 \frac{1}{z} \times \frac{4}{3}\pi r^3$$

Table 1: Substituted Values for the Calculation

Parameter	Value
Redshift, z	1.2×10^{-13}
Gravitational constant, G	$6.67 \times 10^{-11}\,\mathrm{Nm^2/kg^2}$
Speed of light, c	$3 \times 10^8\,\mathrm{m/s}$
Solar radius, r	$4000\,\mathrm{km} = 4 \times 10^6\,\mathrm{m}$
Solar atmosphere density, ρ_0	$10^{-9}\,\mathrm{kg/m^3}$
Initial temperature, T_0	$6000\,\mathrm{K}$

With these substitutions, we get,

$$E = 6.0681 \times 10^{11}\ \text{Joules}$$

For diatomic gas like hydrogen, the ratio $\frac{c_p}{c_v}$ is taken to be 1.4. Using known values, we can calculate the total energy lost by photons as they travel through the corona. For a solar radius $r = 4000\,\mathrm{km}$ and an initial temperature of $T_0 = 6000\,\mathrm{K}$, we estimate the outer corona temperature to be,

$$T_E = 4.79\,\text{Million Kelvins (approx.)}$$

7 Conclusion

This paper provides a unified framework to address the solar limb effect and the coronal heating problem. By introducing an energy loss mechanism based on gravitational surface tension, we can explain the redshift of non-scattered photons and the temperature anomalies observed in the solar corona. Our model offers a new perspective on photon-plasma interactions in the Sun's outer atmosphere and suggests that photon energy dissipation plays a significant role in heating the corona.

References

[1] James A. Klimchuk. "On Solving the Coronal Heating Problem". In: *Solar Physics* 234.1-2 (2006), pp. 41–77. DOI: `10.1007/s11207-006-0055-z`.

[2] C. Ortiz and Raju S. Khatiwada. "Gravitational friction from d'Alembert's principle". In: *Scientific Reports* 13.1 (June 2023), p. 10364. ISSN: 2045-2322. DOI: `10.1038/s41598-023-36977-6`. URL: `https://doi.org/10.1038/s41598-023-36977-6`.

[3] J. Halm. "Über eine bisher unbekannte Verschiebung der Fraunhoferschen Linien des Sonnenspektrums". In: *Astronomische Nachrichten* 173.18 (Jan. 1907), p. 273.

[4] Walter S. Adams. “An Investigation of the Displacements of the Spectrum Lines at the Sun’s Limb”. In: *The Astrophysical Journal* 31 (1910), p. 30. DOI: `10.1086/141722`.

[5] F. Zwicky. “On the Red Shift of Spectral Lines through Interstellar Space”. In: *Proceedings of the National Academy of Sciences* 15.10 (Oct. 1929), pp. 773–779.

[6] Robert J. Rutten. “Radiative Transfer in Stellar Atmospheres: A New Look”. In: 203 (2001), pp. 273–285. DOI: `10.1023/A:1012724905976`.

[7] B. De Pontieu et al. “Observing the Roots of Solar Coronal Heating: Chromospheric Alfvénic Waves and Their Possible Role in Energy Transport”. In: *The Astrophysical Journal* 701.2 (2009), pp. L1–L6. DOI: `10.1088/0004-637X/701/2/L1`.

[8] Paola Testa, Steven H. Saar, and Jeremy J. Drake. “Stellar activity and coronal heating: an overview of recent results”. In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 373.2042 (2015), p. 20140259.

[9] James C. Lopresto, Charles Schrader, and A. K. Pierce. “Solar Gravitational Redshift from the Infrared Oxygen Triplet”. In: *The Astrophysical Journal* 376 (Aug. 1991), p. 757.

[10] S. Chandrasekhar. *Radiative Transfer*. New York: Dover Publications, 1960. ISBN: 978-0486605906.

[11] H. B. Callen. *Thermodynamics and an Introduction to Thermostatistics*. 2nd. Wiley, 1985. ISBN: 978-0471862567.

[12] G. B. Rybicki and A. P. Lightman. *Radiative Processes in Astrophysics*. Wiley-VCH, 1979. ISBN: 978-0471058984.

[13] C. Ortiz. “Surface Tension: Accelerated Expansion, Coincidence Problem & Hubble Tension”. In: *International Journal of Modern Physics D* 29.16 (2020), p. 2050115.