Unified Electromagnetic Theory of Matter and Light

Section B — **Structure of Light**

Part B4 – **Electromagnetic Wave Inertia**

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Abstract

This paper develops a structural description of electromagnetic-wave inertia, energy transfer, and gravitational interaction within the framework of coherent electromagnetic-wave chains. Electromagnetic radiation is treated as a propagating physical structure possessing finite transverse dimensions, internal electromagnetic binding, kinetic energy, and momentum.

The proposed model distinguishes gradual attenuation from structural collapse during interactions with matter and relates changes in wave energy to adjustments of its transverse radius and coherent chain length. The inertia associated with electromagnetic field energy provides the basis for examining gravitational energy exchange and momentum transfer.

Solar light deflection is described through two physically distinct mechanisms: direct gravitational interaction with electromagnetic-wave inertia and geometrical deformation of the wavefront caused by spatial variations in the effective electromagnetic properties of the surrounding field. Their contributions are combined in the weak-field approximation.

Using the observed deflection coefficient of 1.84 ± 0.24 arcseconds reported by the Modern Eddington Experiment 2024, the model yields a phenomenological geometrical coupling coefficient of α = 2.20 ± 0.55. The resulting combined deflection is consistent with the selected observation, while the separation into two mechanisms remains a theoretical interpretation requiring independent verification.

The analysis establishes quantitative relationships between electromagnetic-wave energy, inertia, structural dimensions, and external-field response. It extends the structural electromagnetic framework developed in Parts B1–B3 and identifies independent determination of the effective electromagnetic coupling as a central objective for further theoretical and experimental investigation.

1. Introduction

An electromagnetic wave carries energy and momentum and can transfer both to matter during absorption, reflection, or scattering. Its propagation may also be influenced by external gravitational fields. These phenomena are well established experimentally, but their interpretation depends on the physical

description adopted for electromagnetic radiation.

The present article continues the structural electromagnetic-wave model developed in Parts B1 and B2. In this model, an electromagnetic wave is represented as a spatially organized field structure with a characteristic transverse radius R, longitudinal wavelength λ, and electromagnetic energy W. The transverse dimensions and longitudinal periodicity are treated as distinct properties, allowing changes in wave energy and propagation conditions to be examined separately.

Part B2 investigated the transverse stability, interaction, and possible merging of coherent electromagnetic structures. It introduced an approximate energy-radius relation in which increasing energy can produce transverse expansion while characteristic saturated field amplitudes remain approximately unchanged. Part B3 subsequently examined the interaction of these structures with atomic electrons in the photoelectric effect.

Part B4 extends this framework in three directions.

First, the article examines electromagnetic-wave inertia and the transfer of energy and momentum during interaction with matter. Particular attention is given to the distinction between gradual attenuation, geometrical adjustment, and complete loss of structural coherence. The proposed model allows an electromagnetic structure to retain its organized form over a broad range of energies, while sufficiently severe energy loss may lead either to structural collapse or to a reduction in the number of coherent wave periods.

Second, the article investigates how external scalar fields, introduced in Part A4, may influence electromagnetic propagation. Their effect is represented through a spatial variation of the effective product $\varepsilon\mu$, which determines the propagation velocity and wavelength. Within a specified stationary reference frame, the frequency is taken to remain constant while the wavelength changes. A coherent wave chain consequently adjusts its longitudinal length without necessarily changing the number of constituent wave periods.

Third, the article examines the propagation of electromagnetic waves near the Sun. Two distinct mechanisms of light deflection are proposed. The first is a direct gravitational interaction with the energy and momentum of the propagating wave. Gravitational work changes its energy and consequently its transverse dimensions, while the transverse component of gravitational force changes its direction. The second mechanism is geometrical: a spatial gradient of the effective electromagnetic propagation parameter changes the direction of the wave without requiring direct gravitational work.

These mechanisms are developed separately because their physical origins and effects on wave structure are different. Their angular contributions are combined in the weak-field approximation. The resulting model is evaluated through the observed magnitude and distance dependence of solar light deflection. The phenomenological coupling parameter describing the geometrical contribution is determined empirically, while its proposed origin in nonlinear electromagnetic field geometry remains a subject for further investigation.

The objective of Part B4 is therefore to connect electromagnetic-wave inertia, energy transfer, structural evolution, and gravitational propagation within a common physical framework. By distinguishing energy exchange from geometrical changes of wave propagation, the article develops quantitative relations for wave energy, transverse radius, wavelength, coherent-chain length, and solar light deflection, together with experimentally testable consequences.

2. Energy, Inertia, and Momentum of an EM Wave

2.1. Positive and Negative Energy Contributions

The electromagnetic-wave model developed in the preceding articles distinguishes between two energy contributions associated with the electric and magnetic fields.

The positive energy W_p represents an energy contribution capable of performing work. When this energy performs work on its surroundings, its available magnitude decreases. The process can continue until the positive energy contribution approaches zero.

The negative energy W_v has a different physical role. It represents binding energy associated with the electromagnetic structure. A system possessing negative binding energy requires an external energy input to overcome the binding and reach the reference state of zero binding energy.

Thus, the two contributions differ not only in sign but also in their physical response to energy transfer.

For a freely propagating electromagnetic wave, the proposed model assumes an approximate balance:

$$W_p + W_v \approx 0$$

This relation expresses the balance between the positive and negative internal energy contributions. It does not imply that the electromagnetic structure has no inertia or that it cannot transfer energy to surrounding matter.

The electric and magnetic fields possess positive local energy-density magnitudes, conventionally expressed as

$$u_E = \frac{\varepsilon_0 E^2}{2}$$

$$u_B = \frac{B^2}{2\mu_0}$$

The corresponding positive magnitudes can be obtained by integration over the electromagnetic structure:

$$W_p = \int_V u_E \, dV$$

$$|W_v| = \int_V u_B \, dV$$

In the proposed model, the negative sign assigned to W_v describes its binding contribution to the internal energy balance. Its magnitude remains positive and contributes to the inertia of the structure.

The distinction between signed energy and positive energy-density magnitude is essential for the following analysis.

2.2. Inertia of the Electromagnetic Structure

The proposed model associates inertia with both electromagnetic energy contributions.

Although the positive and negative energies may nearly cancel in their signed internal balance, their contributions to inertia are taken to be additive in magnitude.

Accordingly, the inertial mass of the electromagnetic structure is defined as

$$m_i = \frac{W_p + |W_v|}{c^2}$$

For a freely propagating wave satisfying

$$W_p \approx |W_v|$$

the inertial mass becomes approximately

$$m_i \approx \frac{2W_p}{c^2}$$

Thus, an approximately zero signed internal-energy balance does not imply zero inertia.

The model interprets this inertia as a property of the complete electromagnetic structure rather than of either field contribution separately.

The positive energy contributes through its capacity to perform work, while the negative

binding energy contributes through the energy required to overcome its binding action.

Both contributions therefore participate in determining the resistance of the propagating electromagnetic structure to changes in its momentum.

The quantity m_i is an effective inertial mass associated with propagation. It is not introduced as the rest mass of a stationary electromagnetic wave.

2.3. Kinetic Energy of Propagation

A freely propagating electromagnetic wave possesses energy associated with its motion.

In the proposed model, the transferable energy of the wave is identified with the kinetic energy of its propagating electromagnetic structure.

This energy is defined as

$$W_k = m_i c^2$$

Using the preceding definition of inertia gives

$$W_k = W_p + |W_v|$$

Consequently, the positive and negative internal energy contributions are not counted again as additional contributions to the total transferable energy.

The distinction is expressed by two separate relations:

$$W_{\text{int}} = W_p + W_v \approx 0$$

$$W_k = W_p + |W_v| > 0$$

The first relation describes the signed internal-energy balance. The second defines the positive kinetic energy associated with propagation.

Although the two expressions contain the same energy contributions, they describe different physical properties of the model.

In particular, the negative binding energy does not itself represent a freely available positive energy reserve. Removing the binding requires work. Its absolute magnitude nevertheless contributes positively to the inertia and consequently to the kinetic energy assigned to the propagating structure.

This interpretation identifies W_k as the energy available for transfer when the organized electromagnetic propagation is interrupted or transformed through interaction with matter.

The precise distribution of transferred energy among mechanical motion, thermal excitation, radiation, and structural reorganization depends on the interaction process and is examined in the following chapter.

2.4. Electromagnetic Momentum and Energy Flux

An electromagnetic wave transports momentum together with its energy.

In classical electromagnetic theory, the Poynting vector describes the local energy flux:

$$S = \frac{1}{\mu_0} E \times B$$

The associated electromagnetic momentum density in vacuum is

$$g = \frac{S}{c^2}$$

The total electromagnetic momentum is therefore expressed as

$$p = \frac{1}{c^2} \int_V \mathrm{b}S \; dV$$

For a predominantly longitudinally propagating structure, the model adopts the relation

$$p = \frac{W_k}{c}$$

Together with the kinetic-energy relation,

$$W_k = m_i c^2$$

this gives

$$p = m_i c$$

The three quantities are therefore connected:

$$m_i = \frac{W_p + |W_v|}{c^2}$$

$$W_k = m_i c^2$$

$$p = m_i c$$

These relations describe the proposed connection between electromagnetic-field inertia, kinetic energy, and the momentum of the propagating wave.

The Poynting vector also describes internal redistribution of electromagnetic energy.

Its longitudinal component transports energy along the propagation direction, while transverse components may redirect energy within the wave structure.

Depending on the local electric and magnetic field geometry, transverse energy transport may contribute to radial contraction or expansion.

The nonlinear radial distribution of the electric field, together with the associated magnetic-field response, is therefore relevant to the stability of the wave structure.

These internal processes must be distinguished from changes in the direction of the wave as a whole. A redistribution of energy within the structure does not necessarily produce a change in its total momentum.

2.5. Energy and Momentum Conservation

The proposed distinction between signed internal energy and kinetic energy provides the basis for describing interactions between electromagnetic waves and matter.

When an electromagnetic wave encounters a material object, its propagating structure may undergo absorption, reflection, scattering, transmission, or partial disruption.

For complete absorption, the incident electromagnetic structure no longer continues as an independently propagating wave. Its incident energy and momentum must be accounted for in the combined material and electromagnetic system.

The energy available from the incident wave is represented by

$$W_k = m_i c^2$$

while its incident longitudinal momentum is

$$p = \frac{W_k}{c}$$

For a completely absorbing target initially at rest, the transferred energy is approximately

$$Q = W_k$$

when the small recoil kinetic energy is included in the total energy balance or neglected in the thermal approximation.

The corresponding momentum transfer is

$$\Delta p = \frac{W_k}{c}$$

Reflection produces a different momentum transfer because the outgoing electromagnetic structure retains energy and reverses its longitudinal direction.

Partial absorption and scattering require separate accounting of the outgoing electromagnetic energy and momentum.

At the structural level, the interaction may also change the balance between W_p and W_v. A sufficiently strong disturbance can disrupt the organization of the propagating wave.

The negative binding contribution does not disappear merely because the structure is interrupted. Any transformation of the bound configuration must be included in the energy balance, together with the work required to overcome or reorganize the binding.

The resulting energy transfer must therefore be evaluated for the complete interacting system rather than by independently adding the magnitudes of the internal energy contributions to the kinetic energy.

The present model consequently distinguishes three related aspects of electromagnetic propagation: the signed balance of internal

energy, the positive inertia and kinetic energy associated with motion, and the transport of momentum through the electromagnetic field.

These relations provide the basis for the following analysis of absorption, reflection, attenuation, and structural collapse. [1], [2], [3]

3. Energy Transfer During Interaction with Matter

3.1. Interaction of an EM Wave with a Material Surface

When an electromagnetic wave reaches a material surface, its propagating field structure interacts with the electric and magnetic properties of the material.

In the proposed model, the incident wave possesses kinetic energy associated with its motion, while its internal positive and negative energy contributions remain approximately balanced. The interaction with matter may change the propagation direction, transfer part of the wave energy to the material, or disrupt the organized electromagnetic structure.

The outcome depends on the electromagnetic response of the surface, the spatial distribution of the incident fields, and the conditions under which the wave encounters the material.

Four basic outcomes can be distinguished: absorption, reflection, transmission, and scattering. In practice, several of these processes may occur simultaneously.

The energy balance for a stationary material target can be written as

$$W_{k,\mathrm{in}} = W_{k,\mathrm{refl}} + W_{k,\mathrm{trans}} + W_{k,\mathrm{scat}} + W_{\mathrm{mat}}$$

Here, the outgoing terms represent the energies carried away by reflected, transmitted, and scattered electromagnetic structures. The quantity W_{mat} represents the energy retained by the material, including thermal excitation, internal structural changes, and mechanical recoil.

This relation provides the general energy balance for the interaction. It does not require that all incident electromagnetic energy be converted directly into heat.

3.2. Complete Absorption and Energy Conversion

Consider an electromagnetic wave incident on an ideal absorbing surface.

In the case of complete absorption, no coherent electromagnetic structure continues beyond the interaction region, and no reflected or transmitted electromagnetic energy remains.

The incident kinetic energy is transferred to the material system:

$$W_{\mathrm{mat}} = W_{k,\mathrm{in}}$$

For a sufficiently massive target whose recoil energy is negligible, the transferred energy may be approximated as heat or internal excitation:

$$Q \approx W_{k,\mathrm{in}}$$

The incident wave also transfers longitudinal momentum:

$$\Delta p = \frac{W_{k,\mathrm{in}}}{c}$$

The material acquires this momentum through mechanical recoil, support forces, or internal redistribution of momentum.

In the structural interpretation, complete absorption corresponds to the disappearance of the incident wave as an independently propagating coherent structure.

This disappearance does not imply destruction of energy. Instead, the organized electromagnetic motion is transformed into other forms of energy within the material and its surroundings.

The internal binding contribution W_v must also be considered during this transformation.

Because W_v represents negative binding energy, removing its binding effect requires energy. The sum of *Wv* and *Wp* is equal to zero. Consequently, structural disintegration cannot be understood as the independent release of both the positive and absolute negative energy contributions.

The total transferred energy is the incident kinetic energy W_k, already defined through the inertial properties of the complete electromagnetic structure. The internal contributions are therefore not counted again.

The detailed mechanism by which the positive and binding field contributions nullify during absorption remains a separate dynamical question.

3.3. Reflection and Momentum Transfer

Reflection differs from absorption because an outgoing electromagnetic structure remains after the interaction.

For an ideal stationary reflecting surface, the incident and reflected electromagnetic energies are approximately equal:

$$W_{k,\mathrm{refl}} \approx W_{k,\mathrm{in}}$$

At normal incidence, the propagation direction reverses. The momentum of the reflected wave is therefore opposite to that of the incident wave.

The total momentum transferred to the reflecting surface is

$$\Delta p = \frac{2W_{k,\mathrm{in}}}{c}$$

This is twice the momentum transferred by complete absorption of the same incident energy.

For a continuous beam of power P, the corresponding forces are

$$F_{\mathrm{abs}} = \frac{P}{c}$$

$$F_{\mathrm{refl}} = \frac{2P}{c}$$

These expressions describe ideal absorption and ideal reflection at normal incidence.

In the structural model, reflection involves a reorganization of the electromagnetic field near the material boundary. The incident propagation is replaced by an outgoing configuration with reversed longitudinal momentum.

This process does not require a permanent loss of electromagnetic energy or destruction of the coherent wave organization.

The microscopic field dynamics responsible for reflection depend on the material response and boundary conditions. The present analysis therefore uses energy and momentum conservation to describe the resulting interaction without assuming a unique microscopic restructuring mechanism.

3.4. Partial Absorption, Transmission, and Scattering

Most real materials are neither perfect absorbers nor perfect reflectors.

An incident electromagnetic wave may distribute its energy among several outgoing components while transferring part of its energy to the material.

Let the absorption, reflection, and transmission fractions be denoted by A, R, and T, respectively. If scattering is included explicitly through a fraction D, energy conservation requires

$$\mathrm{A} + R + \mathrm{T} + \mathrm{D} = 1$$

All four quantities are defined as nonnegative fractions of the incident electromagnetic energy.

The energy retained by the material is

$$W_{\mathrm{mat}} = AW_{k,\mathrm{in}}$$

The energy carried by the reflected component is

$$A + R_f + T + D = 1$$

Analogous expressions apply to transmission and scattering.

These relations describe the macroscopic energy distribution. They do not determine whether the surviving electromagnetic field remains one coherent structure or is reorganized into several independently propagating structures.

In the proposed model, this distinction is important.

A partially transmitted wave may retain its original coherent organization with reduced energy and a correspondingly modified transverse radius. Alternatively, interaction with the material may produce fragmentation, scattering, or a loss of coherence.

The final configuration depends on the electromagnetic properties of the material and on the stability conditions discussed in Part B2.

Consequently, attenuation of electromagnetic energy and destruction of the coherent wave structure must be treated as different phenomena.

3.5. Radiation Pressure and Experimental Consistency

The transfer of electromagnetic momentum produces a mechanical force on matter.

For a beam incident normally on a surface of area A_s, the incident power is

$$P = IA_s$$

where I is the time-averaged incident intensity.

For complete absorption, the radiation pressure is

$$P_{\text{rad,abs}} = \frac{I}{c}$$

For ideal reflection, the radiation pressure becomes

$$P_{\text{rad,refl}} = \frac{2I}{c}$$

These relations agree with the established momentum-transfer description of electromagnetic radiation.

For a surface with partial absorption and reflection, and with no transmitted or scattered component, the pressure is

$$P_{\text{rad}} = \frac{I}{c}(A + 2\mathcal{R})$$

More generally, transmitted and scattered radiation must be included through their outgoing momentum components.

In the proposed model, radiation pressure represents a direct mechanical manifestation of the kinetic energy and momentum of the propagating electromagnetic structure.

The approximate internal balance

$$W_p + W_v \approx 0$$

does not eliminate the mechanical effect, because the momentum depends on the positive kinetic energy

$$W_k = W_p + |W_v|$$

The interaction with matter therefore provides an important consistency requirement for the proposed distinction between internal binding energy and propagation energy.

Any structural description of the electromagnetic wave must reproduce the measured energy transfer and radiation pressure while also accounting for possible changes in coherence and transverse geometry.

The analysis developed in this chapter establishes the macroscopic energy and momentum balances. The next chapter examines the structural consequences of interactions in greater detail, including gradual attenuation, changes of transverse radius, and complete loss of coherent electromagnetic organization. [1],[2],[3]

4. Attenuation and Structural Stability

4.1. Energy Loss Without Structural Collapse

An electromagnetic wave interacting with matter or external fields may lose part of its kinetic energy without necessarily losing its coherent organization.

In the proposed model, attenuation and structural collapse represent two distinct processes. Attenuation describes a reduction in the energy of a propagating electromagnetic structure while its organized electric and magnetic field configuration remains sufficiently stable to continue propagation. Structural collapse occurs when this organization can no longer be maintained.

The kinetic energy of the propagating structure is defined as

$$W_k = W_p + |W_v|$$

where the positive and negative internal energy contributions remain approximately balanced:

$$W_p + W_v \approx 0$$

During gradual attenuation, both field contributions may decrease in magnitude while preserving approximately the same internal balance. Their reduction decreases the kinetic energy and effective inertia of the propagating structure.

For a coherent wave chain, the kinetic energy may be represented approximately as

$$W_k = C_u u_s R^2 L$$

where u_s is the characteristic energy density of the saturated electromagnetic structure, R is its transverse radius, L is the length of the coherent chain, and C_u is a geometrical factor describing the spatial field distribution.

This expression applies when the characteristic saturated energy density and geometrical profile remain approximately unchanged.

Energy loss can then be accommodated through changes in the dimensions of the coherent structure, without requiring an immediate loss of electromagnetic coherence.

4.2. Transverse Radius Reduction

Part B2 introduced the approximate quadratic relationship between the energy and transverse radius of geometrically similar saturated electromagnetic structures.

For a coherent wave chain of fixed longitudinal length, this gives

$$W_k \propto R^2$$

Consequently, a decrease in kinetic energy produces a reduction in transverse radius:

$$R_2 = R_1 \sqrt{\frac{W_{k,2}}{W_{k,1}}}$$

This response allows the electromagnetic structure to preserve its characteristic saturated field amplitudes while its total energy decreases.

A small fractional energy loss therefore produces approximately half as large a fractional reduction in radius:

$$\frac{dR}{R} \approx \frac{1}{2}\frac{dW_k}{W_k}$$

The expression assumes that the longitudinal length and characteristic energy density remain unchanged during the adjustment.

In a spatially varying propagation environment, the wavelength and chain length may also change. The more general geometrical energy relation is then

$$\frac{dW_k}{W_k} = 2\frac{dR}{R} + \frac{dL}{L}$$

This equation distinguishes transverse structural adjustment from longitudinal deformation.

The model does not require that all energy changes produce fragmentation or a reduction in the number of coherent wave periods. Over

a broad energy range, transverse radius adjustment is assumed to be the dominant response.

4.3. Role of the Poynting Vector in Radial Redistribution

The internal stability of the electromagnetic structure depends not only on the total energy but also on its spatial distribution and the directions of electromagnetic energy transport.

The Poynting vector is

$$S = \frac{E \times B}{\mu_0}$$

Its longitudinal component transports energy along the propagation direction, while its transverse component describes redistribution of energy across the wave structure.

In the proposed geometry, the radial component of the energy flux may change direction as the relative electric and magnetic field distributions evolve.

An inward radial energy flow can contribute to concentrating electromagnetic energy toward the inner region of the structure. An outward radial energy flow can redistribute energy toward larger transverse distances.

These processes are associated with the contraction and expansion tendencies investigated in Part B2.

The radial organization is also influenced by nonlinear field distributions, particularly the radial variation of the electric field and the magnetic response near the outer boundary.

The stability of the wave therefore depends on a balance between the radial energy redistribution and the corresponding electromagnetic stresses.

For a locally conserved electromagnetic field in vacuum, the energy continuity equation is

$$\frac{\partial u}{\partial t} + \nabla \cdot \vec{S} = 0$$

This relation expresses the connection between local energy-density changes and the divergence of the energy flux.

A radial redistribution of energy does not by itself imply a change in the total kinetic energy of the wave. Internal energy transport may reorganize the electromagnetic structure while preserving the total energy.

Conversely, sustained energy transfer outside the coherent structure can reduce its kinetic energy and lead to attenuation.

Thus, the direction of the Poynting vector participates in determining the spatial evolution of the electromagnetic structure, while the total energy balance determines whether that evolution involves attenuation.

4.4. Stability of Coherent Wave Chains

Part B1 introduced the possibility that electromagnetic-wave structures may form coherent longitudinal chains during propagation.

A coherent chain can be described through its longitudinal length L, wavelength λ, and number of coherent wave periods N:

$$L = N\lambda$$

Over a broad range of kinetic energies, the proposed model assumes that the number of coherent periods remains approximately constant.

Therefore,

$$N = \text{const.}$$

The chain may undergo changes in wavelength and length while retaining the same number of periods:

$$\frac{L_2}{L_1} = \frac{\lambda_2}{\lambda_1}$$

Such longitudinal deformation does not necessarily imply a change in the number of coherent wave structures.

At the same time, energy changes may be accommodated through transverse radius adjustment, allowing the chain to retain its internal organization.

The coherent structure therefore has two distinct geometrical responses: transverse adjustment associated with changes in kinetic energy and longitudinal adjustment associated with changes in wavelength.

These responses may occur simultaneously while preserving the continuity of the electromagnetic field.

The relation between energy, transverse radius, and chain length provides a common geometrical framework for describing both processes.

4.5. Structural Collapse at Extremely Low Energy

The preceding analysis assumes that a coherent electromagnetic structure can remain stable as its transverse radius decreases.

However, this assumption need not remain valid at arbitrarily low energies.

At sufficiently small kinetic energy, the electromagnetic field configuration may no longer support the radial organization required for coherent propagation.

The resulting loss of stability may involve changes in the electric and magnetic field profiles, disappearance of the transverse restoring tendency, or failure of the organized displacement-current configuration considered in Part B2.

The model therefore allows the possibility of a critical low-energy regime in which ordinary transverse adjustment is no longer sufficient.

The existence of such a regime does not require that a universal minimum transverse radius be specified in advance.

A critical condition may depend on wavelength, the nonlinear radial field profile, and the stability of the complete coherent structure.

The transition should therefore be understood as a structural stability problem rather than as a purely geometrical size limit.

If coherence is lost, the incident wave no longer survives as the same organized electromagnetic structure. Its remaining energy and momentum must nevertheless be conserved through the resulting electromagnetic disturbances and interactions with the surrounding environment.

4.6. Two Possible End States of a Coherent Chain

When the kinetic energy becomes extremely small, the proposed model considers two possible responses.

The first possibility is the collapse of the entire coherent chain. In this case, the organized electromagnetic structure loses the conditions required for continued coherent propagation. Its remaining energy is redistributed into other electromagnetic configurations or transferred to the surrounding environment.

The second possibility is a reduction in the number of coherent wave periods. Instead of losing coherence as a whole, the chain may reorganize into a shorter structure containing fewer periods.

The longitudinal relation remains

$$L = N\lambda$$

but, in this regime, N is no longer assumed constant.

A reduction in N may allow the remaining coherent part of the chain to retain a stable field configuration while the energy associated with the removed portion is redistributed.

The limiting possibility of a single remaining wave period may be represented as

$$N = 1$$

This is a proposed structural limiting configuration, not an established universal lower bound for electromagnetic propagation.

The model does not yet determine which of the two processes is preferred or the precise energy at which the transition occurs.

Both possibilities require a more complete dynamical analysis of the electromagnetic field configuration and its stability.

For the moderate and weak energy changes considered in the following gravitational analysis, the coherent wave chain is assumed to remain well within its stable regime. Its number of periods remains unchanged, while its transverse radius and longitudinal dimensions adjust to the local propagation conditions.

The distinction between attenuation, reversible geometrical adjustment, and structural collapse is therefore central to the proposed model. It allows electromagnetic waves to undergo substantial changes in energy and geometry without necessarily losing their coherent organization, while also providing a framework for investigating the possible disappearance or fragmentation of extremely weak electromagnetic structures. [1], [2], [3]

5. External Scalar Fields and EM-Wave Propagation

5.1. Two Independent External Scalar Fields

Part A4 introduced a model in which electromagnetic structures generate two external scalar fields associated with positive and negative binding energy contributions.

The positive contribution W_p is associated with an outward, repulsive tendency, while the negative contribution W_v is associated with an attractive binding tendency. The two fields are assumed to propagate independently and to combine through their effects on matter and electromagnetic structures.

Although the positive and negative internal energy contributions of a freely propagating electromagnetic wave may approximately balance, their absolute magnitudes remain nonzero. Consequently, their physical effects cannot be inferred solely from the algebraic sum of their signed energies.

The same distinction applies to external fields generated by matter. Their combined influence depends on their spatial distributions, their different physical effects, and the response of the electromagnetic structure exposed to them.

The present article does not attempt to repeat the gravitational field construction developed in Part A4. Instead, it examines a specific consequence: the possibility that external scalar fields modify the propagation conditions of electromagnetic waves.

5.2. Effective Electromagnetic Properties of Space

The propagation of electromagnetic waves depends on the electric and magnetic response of the environment.

In a linear, isotropic, nondispersive medium, the phase velocity is determined by the product of permittivity and permeability:

$$v = 1/\sqrt{\varepsilon\mu}$$

In vacuum, the corresponding relation is

$$c = 1/\sqrt{\varepsilon_0\mu_0}$$

The proposed model extends this description by introducing effective electromagnetic propagation parameters that depend on the external scalar-field environment.

These parameters are denoted by $\varepsilon_{\mathrm{eff}}(r)$ and $\mu_{\mathrm{eff}}(r)$.

The model does not require their individual changes to be specified. Instead, it introduces the dimensionless product

$$K(r) = \varepsilon_{\text{eff}}(r)\mu_{\text{eff}}(r)/(\varepsilon_0\mu_0)$$

The corresponding propagation velocity becomes

$$v(r) = c/\sqrt{K(r)}$$

The quantity $K(r)$ therefore describes the combined effect of the external environment on electromagnetic propagation.

A value $K = 1$ corresponds to the reference vacuum conditions. A value $K > 1$ corresponds to a lower effective propagation velocity, while $K < 1$ corresponds to a higher effective propagation velocity within the selected coordinate description.

The proposed dependence should be understood as an effective description of electromagnetic-wave propagation in an external field, rather than as a demonstrated change in the locally measured vacuum constants.

5.3. Geometrical Response of an EM Wave

Parts B1 and B2 describe electromagnetic waves as organized structures whose transverse dimensions depend on their energy and field geometry.

Their propagation is determined not only by the local electric and magnetic field amplitudes but also by the spatial organization of the complete electromagnetic structure.

The proposed model assumes that external scalar fields can influence this organization through changes in the effective propagation conditions.

The resulting variation of $K(r)$ modifies the wavelength and phase velocity. In a stationary external-field configuration, the wave frequency is taken to remain constant within the selected common time coordinate.

Consequently,

$$v(r) = f\lambda(r)$$

and therefore

$$\lambda(r) = c/\left(f\sqrt{K(r)}\right)$$

The wavelength changes as the wave moves through regions with different values of K, even when the frequency remains unchanged.

This mechanism is geometrical. A stationary, nondissipative variation of K does not, by itself, require gravitational work to be performed on the propagating electromagnetic structure.

The model therefore distinguishes between changes in propagation geometry and changes in wave energy caused by direct gravitational interaction.

The former primarily modify wavelength, propagation velocity, and direction. The latter modify kinetic energy, inertia, and the structural dimensions associated with energy.

Both effects may occur simultaneously, but they are treated as physically distinct mechanisms.

5.4. Phenomenological Coupling Coefficient

A complete calculation of the effective electromagnetic response would require a quantitative description of the nonlinear field geometry and its interaction with the external scalar fields.

Such a calculation has not yet been developed.

The present model therefore introduces a phenomenological coefficient α, representing the combined influence of these nonlinear geometrical effects on electromagnetic propagation.

For a spherically symmetric gravitational source, the weak-field approximation is written as

$$K(r) = 1 + \alpha GM/(rc^2)$$

where G is the gravitational constant, M is the source mass, r is the radial distance from its center, and c is the reference vacuum propagation velocity.

The coefficient α is dimensionless.

It is not assumed to be independently calculable from the present structural equations. Instead, its numerical value is constrained empirically through observations of electromagnetic-wave propagation.

The proposed physical origin of α lies in the nonlinear geometrical response of the electromagnetic structure to the external scalar-field environment.

This interpretation provides a possible connection between the structural wave model and observed gravitational effects while leaving the detailed microscopic calculation for future investigation.

5.5. Weak-Field Approximation

For a weak gravitational field, introduce the dimensionless parameter

$$q(r) = GM/(rc^2)$$

The effective propagation parameter becomes

$$K(r) = 1 + \alpha q(r)$$

For sufficiently small q, the propagation velocity may be expanded to first order:

$$v(r) \approx c(1 - \alpha q(r)/2)$$

Similarly, for constant frequency in the selected stationary reference frame,

$$\lambda(r) \approx \lambda_\infty(1 - \alpha q(r)/2)$$

Here, λ_∞ denotes the wavelength in the reference region where the external gravitational influence becomes negligible.

These expressions show that, for positive α, both the effective propagation velocity and wavelength decrease toward the gravitational source.

The approximation is particularly suitable for propagation near the Sun, where the dimensionless gravitational parameter remains very small outside the solar surface.

A spatial gradient of K also produces a gradient in propagation velocity. Under the geometrical-optics approximation, this gradient can change the direction of electromagnetic-wave propagation.

The resulting path deflection is examined separately from the direct gravitational interaction with the kinetic energy and momentum of the wave.

The present chapter therefore establishes the geometrical propagation mechanism required for the following analysis. [3]–[4]

6. Geometrical Deformation of EM-Wave Propagation

6.1. Spatially Nonuniform Propagation Conditions

An electromagnetic wave propagating through an external scalar-field environment may encounter spatially nonuniform electromagnetic conditions.

Section 5 introduced the effective parameter

$$K(r) = \varepsilon_{\text{eff}}(r)\mu_{\text{eff}}(r)/(\varepsilon_0\mu_0)$$

which represents the combined influence of the external fields on electromagnetic propagation.

For a spherically symmetric gravitational source, the proposed weak-field approximation is

$$K(r) = 1 + \alpha GM/(rc^2)$$

The parameter K varies with distance from the source. Consequently, different transverse regions of a spatially extended electromagnetic structure may experience slightly different propagation conditions.

When an electromagnetic wave passes near a massive body, its inner side is closer to the source than its outer side.

For a positive coupling coefficient, this gives

$$K_{\text{inner}} > K_{\text{outer}}$$

The electromagnetic structure is therefore exposed to a transverse gradient of the external propagation conditions.

This gradient introduces a geometrical asymmetry across the wavefront. The resulting structural adjustment is the basis of the geometrical deflection mechanism considered in this chapter.

6.2. Differential Geometrical Response Across the Wavefront

Consider two neighboring transverse regions of a coherent electromagnetic wave, one situated closer to the gravitational source and the other farther away.

Because the effective parameter K differs between these regions, their local electromagnetic phase geometry need not evolve identically.

The model associates this difference with a gradual rotation of the wavefront toward the region of stronger external influence.

The inner and outer regions remain parts of the same continuous electromagnetic structure. Their differential response therefore changes the orientation of the complete wavefront rather than producing two independently propagating waves.

The effect can be understood through the geometrical construction of neighboring wavefronts.

A transverse difference in their spatial development creates a small angular rotation. Successive rotations accumulate along the propagation path and produce a curved trajectory.

The direction of the curvature is determined by the spatial gradient of the effective parameter K.

For the solar gravitational environment, the resulting geometrical contribution is directed toward the Sun.

This mechanism does not require a direct gravitational force acting on the inertial mass of the electromagnetic wave. It arises from the spatially nonuniform propagation geometry associated with the external scalar fields.

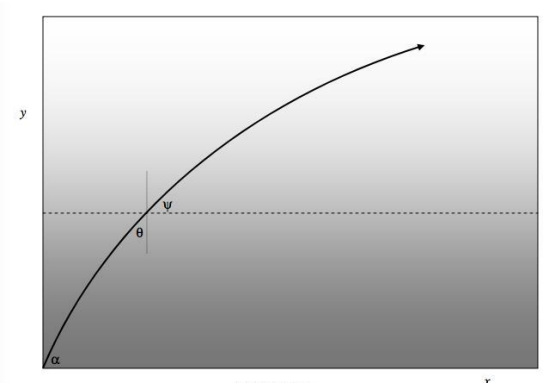

Figure 1 *-A curved propagation path illustrates the gradual change in direction caused by a spatially varying propagation environment. The local angular deviation accumulates along the trajectory, providing a geometrical description of wave deflection in a transverse gradient of K.*

6.3. Curvature of the Propagation Path

The geometrical response can be represented using an effective optical geometry.

Introduce the dimensionless geometrical parameter

$$n(r) = \sqrt{K(r)}$$

Here, n characterizes the spatial propagation geometry associated with the external scalar-field environment.

Let $\mathrm{n}t$ denote the unit tangent to the electromagnetic-wave trajectory, and let s denote distance measured along that trajectory.

The geometrical-optics equation may be written as

$$\frac{d}{ds}(nt) = \nabla n$$

Its component perpendicular to the trajectory determines the local curvature:

$$\frac{dt}{ds} = \nabla_{\perp} \ln n$$

This relation shows that a transverse gradient of the geometrical parameter produces a gradual change in propagation direction.

For a spherically symmetric source, the curvature is directed toward the region where n increases.

Because n is determined by K, the geometrical deflection depends on the spatial variation of the external scalar-field environment.

The relation provides a mathematical description of the curvature without introducing the temporal properties of electromagnetic oscillation.

In a sufficiently weak external field, the curvature is small, and the path can be treated as a nearly straight trajectory with a gradual transverse deviation.

This approximation will be used in Section 8 to calculate the geometrical contribution to solar light deflection.

6.4. Deformation of a Coherent EM-Wave Chain

Parts B1 and B2 introduced a coherent electromagnetic-wave chain as an extended structure whose longitudinal organization is maintained through correlated electromagnetic field configurations.

When such a chain propagates through a spatial gradient of K, different transverse portions experience slightly different geometrical conditions.

The resulting wavefront rotation produces a corresponding change in the orientation of the coherent structure.

The chain may therefore follow a curved trajectory while maintaining continuity of its electromagnetic organization.

The geometrical deformation is not necessarily accompanied by attenuation or structural collapse.

In the proposed model, the coherent chain may retain its constituent organization while undergoing reversible changes in shape and longitudinal arrangement.

Such deformation must be distinguished from the transverse expansion or contraction associated with changes in kinetic energy.

The external geometrical gradient changes the direction and spatial arrangement of the propagating structure. Direct gravitational work, considered in Section 7, changes its kinetic energy and consequently its characteristic transverse dimensions.

The two mechanisms are therefore treated separately even though they may act simultaneously on the same electromagnetic wave.

6.5. Geometrical Deflection Near the Sun

Consider an electromagnetic wave passing the Sun at a minimum distance b from its center.

The Sun generates a spatially varying external scalar-field environment. In the proposed model, this produces a corresponding radial variation of K(r).

The side of the electromagnetic structure closer to the Sun experiences a larger value of K than the opposite side.

The resulting geometrical asymmetry continuously rotates the local wavefront toward the Sun.

As the electromagnetic wave approaches the point of closest passage, the transverse gradient produces a progressively accumulated angular deviation.

After passing the Sun, the geometrical influence remains directed toward the solar center. Its transverse component therefore continues to contribute to the net bending of the trajectory.

Far from the Sun, the gradient becomes small, and the electromagnetic wave approaches a new asymptotic propagation direction.

For the weak-field model introduced in Section 5, the accumulated geometrical deflection is

$$\theta_{\text{geom}} = \alpha GM/(bc^2)$$

where b is the minimum distance of the approximately straight reference trajectory from the center of the Sun.

This result represents only the geometrical contribution associated with the spatial gradient of K.

It does not include the direct gravitational interaction with the kinetic energy and momentum of the electromagnetic structure.

That second mechanism is developed independently in the following chapter and combined with the geometrical contribution only in the quantitative solar-deflection analysis of Section 8.

The geometrical description developed here therefore establishes a distinct mechanism of electromagnetic-wave deflection: a spatially nonuniform external field produces differential deformation across the wavefront, resulting in a curved propagation path without requiring direct gravitational work on the wave. [3],[4]

7. Gravitational Energy Exchange and Structural Response

7.1. Gravitational Work on a Propagating EM Wave

The electromagnetic-wave model developed in the preceding sections assigns inertia to the combined positive and negative binding energy contributions of the electromagnetic structure.

The inertial mass is defined as

$$m_i = \frac{W_p + |W_v|}{c^2}$$

while the kinetic energy associated with propagation is

$$W_k = W_p + |W_v|$$

Consequently,

$$m_i = \frac{W_k}{c^2}$$

The kinetic energy represents the positive electromagnetic energy of the complete propagating structure. It is not an additional energy contribution independent of the electric and magnetic field energies.

Part A4 introduced the hypothesis that the same electromagnetic energy contributions determine both inertial and gravitational mass. Accordingly, the present model assumes

$$m_g = m_i$$

In the following gravitational analysis, the reference vacuum propagation speed c is treated as constant in the energy–inertia relation and in the leading-order momentum calculations. This approximation is adopted because variations of the effective propagation conditions in the weak solar gravitational field are small. Higher-order corrections and the complete dynamical coupling to the spatially varying propagation parameter K are not included in the present treatment.

An electromagnetic wave passing through an external gravitational field is therefore subject to a gravitational force associated with its kinetic energy.

For a spherically symmetric gravitational source of mass M, the magnitude of this force is

$$F_g = \frac{GMm_g}{r^2}$$

Using the proposed equivalence between gravitational and inertial mass gives

$$F_g = \frac{GMW_k}{r^2c^2}$$

The force acts toward the gravitational source. In vector form,

$$\overrightarrow{F_g} = -\frac{GMW_k}{r^2c^2}\hat{r}$$

where r is the distance from the source center and $\hat{r}$ is the outward radial unit vector.

The gravitational interaction may produce two distinguishable effects. The component of the force along the wave displacement performs work and changes its kinetic energy. The component transverse to the propagation direction changes the direction of its momentum.

These effects arise from the direct gravitational interaction with the propagating electromagnetic structure. They are distinguished from the geometrical wavefront deformation associated with the spatial gradient of K, discussed in Section 6.

7.2. Variation of Wave Kinetic Energy

Consider an electromagnetic wave moving through the gravitational field of a spherically symmetric source.

For a small radial displacement dr, gravitational work changes the kinetic energy according to

$$dW_k = \overrightarrow{F_g} \cdot d\vec{r}$$

Since the gravitational force is directed toward the source,

$$dW_k = -\frac{GMW_k}{r^2c^2}dr$$

Dividing by the instantaneous kinetic energy gives

$$\frac{dW_k}{W_k} = -\frac{GM}{r^2c^2}dr$$

Integrating from a reference region far from the gravitational source to a radial position r yields

$$\ln\left(\frac{W_k(r)}{W_{k,\infty}}\right) = \frac{GM}{rc^2}$$

Therefore,

$$W_k(r) = W_{k,\infty}e^{\frac{GM}{rc^2}}$$

Here, $W_{k,\infty}$ denotes the wave kinetic energy in the distant reference region.

The exponential dependence follows from the assumed proportionality between gravitational mass and the instantaneous kinetic energy of the electromagnetic structure.

The equation predicts that the kinetic energy increases as the wave approaches the gravitational source and decreases as it moves outward.

For a wave passing between two arbitrary radial positions r_1 and r_2, the energy ratio is

$$\frac{W_k(r_2)}{W_k(r_1)} = e^{\frac{GM}{c^2}\left(\frac{1}{r_2}-\frac{1}{r_1}\right)}$$

This expression also applies to the energy change along a nonradial path in the assumed stationary, conservative gravitational field, since the gravitational work depends on the initial and final radial positions.

The change is reversible when the gravitational field is stationary and additional losses through absorption, scattering, or structural disruption are negligible.

The relation is derived within the assumed gravitational energy–inertia model and the constant-reference-c approximation. Its extension to strong gravitational fields requires a separate treatment.

7.3. Variation of Inertial and Gravitational Mass

Because the effective inertial mass is related to the kinetic energy by

$$m_i(r) = \frac{W_k(r)}{c^2}$$

a gravitationally induced energy change produces a corresponding change in inertial mass.

Substituting the energy relation gives

$$m_i(r) = m_{i,\infty} e^{\frac{GM}{rc^2}}$$

With the assumed equality of gravitational and inertial mass,

$$m_g(r) = m_i(r)$$

the gravitational response also changes as the electromagnetic structure gains or loses kinetic energy.

The relative changes in kinetic energy and effective inertial mass are equal:

$$\frac{m_i(r)}{m_{i,\infty}} = \frac{W_k(r)}{W_{k,\infty}}$$

This result follows directly from the model's energy–inertia definition.

The kinetic energy and inertial mass are therefore not independent quantities. They represent two related properties of the same propagating electromagnetic configuration.

7.4. Transverse Radius and Volume Adjustment

Part B2 established an approximate relationship between electromagnetic energy and the transverse dimensions of a saturated coherent structure.

For a coherent electromagnetic-wave chain with characteristic saturated energy density u_s, transverse radius R, and longitudinal extent L, the kinetic energy is represented as

$$W_k = C_u u_s R^2 L$$

where C_u is a dimensionless geometrical factor describing the spatial distribution of electromagnetic energy.

The present model assumes that u_s and C_u remain approximately constant during small structural adjustments.

Consequently,

$$R^2 L \propto W_k$$

The corresponding structural relation is

$$\frac{R^2(r)L(r)}{R_\infty^2 L_\infty} = \frac{W_k(r)}{W_{k,\infty}}$$

Substituting the gravitational energy relation gives

$$\frac{R^2(r)L(r)}{R_\infty^2 L_\infty} = e^{\frac{GM}{rc^2}}$$

This equation relates the gravitational energy exchange to the overall dimensions of the coherent electromagnetic structure without requiring a separate specification of its longitudinal deformation.

The transverse radius can therefore be expressed as

$$R(r) = R_\infty \sqrt{\frac{L_\infty}{L(r)}} e^{\frac{GM}{2rc^2}}$$

If the longitudinal dimension remains approximately constant during a particular process,

$$L(r) \approx L_\infty$$

the expression reduces to

$$R(r) \approx R_\infty e^{\frac{GM}{2rc^2}}$$

The constant-length case is a useful limiting approximation rather than a general requirement of the model.

The more general relation allows simultaneous transverse and longitudinal structural adjustments.

7.5. Structural Response During Solar Passage

Consider an electromagnetic wave approaching the Sun, passing near its surface, and subsequently moving away.

As the wave approaches the Sun, gravitational work increases its kinetic energy and effective inertial mass.

The increase in kinetic energy is accompanied by a change in the dimensions of the coherent electromagnetic structure.

At the point of closest approach, the kinetic energy reaches its maximum along the trajectory.

For a wave passing at minimum distance b, the maximum kinetic energy is

$$W_{k,max} = W_{k,\infty} e^{\frac{GM_\odot}{bc^2}}$$

Introduce the dimensionless gravitational parameter

$$q(r) = \frac{GM_\odot}{rc^2}$$

At the solar surface,

$$q(R_\odot) = \frac{GM_\odot}{R_\odot c^2} \approx 2.123 \times 10^{-6}$$

Since this parameter is very small, the exponential function can be approximated by

$$e^q \approx 1 + q$$

The relative increase in kinetic energy near the solar surface is therefore

$$\frac{\Delta W_k}{W_{k,\infty}} \approx 2.123 \times 10^{-6}$$

The effective inertial mass changes by the same relative amount.

Under the assumption of approximately unchanged saturated energy density and geometrical factor, the structural factor R^2L also increases by approximately 2.123 parts per million.

If the chain length remains approximately constant, the corresponding relative increase in transverse radius is

$$\frac{\Delta R}{R_\infty} \approx 1.062 \times 10^{-6}$$

The precise division of the structural change between transverse radius and longitudinal length depends on the response of the coherent wave chain.

The deformation remains small in the solar gravitational field and is assumed not to disturb the overall stability of the electromagnetic structure.

7.6. Energy Recovery After Solar Passage

In a stationary gravitational field, the kinetic energy gained during approach is returned as the electromagnetic wave moves away from the gravitational source.

Consider a wave entering and leaving the gravitational region at equal radial distances from the center of the Sun.

If additional energy losses and structural disruption are negligible, the kinetic energies at the two positions are equal:

$$W_{k,\mathrm{out}} = W_{k,\mathrm{in}}$$

Consequently,

$$m_{i,\mathrm{out}} = m_{i,\mathrm{in}}$$

The structural factor associated with the saturated electromagnetic configuration also returns to its initial value:

$$R_{\mathrm{out}}^2 L_{\mathrm{out}} = R_{\mathrm{in}}^2 L_{\mathrm{in}}$$

The transverse and longitudinal dimensions return individually to their initial values if the structural response is reversible and the external conditions are identical.

This energy recovery follows from the conservative character of the assumed stationary gravitational interaction.

It does not imply that the propagation direction returns to its original orientation.

The transverse gravitational force can produce a cumulative angular deflection even when the wave kinetic energy returns to its initial value.

The interaction therefore has two distinguishable consequences: a reversible exchange of kinetic energy and a lasting change in propagation direction.

The first determines the temporary variation in kinetic energy, effective inertial mass, and structural dimensions. The second contributes

to the solar light deflection analyzed in Section 8.

In much stronger gravitational fields, such as those near black holes, an electromagnetic wave propagating outward may lose kinetic energy until it reaches the minimum energy required for structural stability. Below this threshold, the coherent electromagnetic structure may collapse and cease to exist as an independently propagating wave.

8. Two Mechanisms of Solar Light Deflection

8.1. Geometry of an EM Wave Passing the Sun

Consider an electromagnetic wave propagating past the Sun at a minimum distance b from its center.

The trajectory is described in a coordinate system in which the initial propagation direction is approximately parallel to the x-axis. The transverse coordinate y measures the displacement from the initial direction, and the solar center is taken as the origin.

In the weak-field approximation, the wave trajectory differs only slightly from a straight line. The radial distance from the Sun can therefore be approximated by

$$r(x) = \sqrt{x^2 + b^2}$$

This geometry provides the basis for calculating the accumulated angular deflection.

The proposed model distinguishes two physical processes capable of changing the propagation direction.

The first is a direct gravitational interaction with the inertia and momentum of the electromagnetic structure.

The second is a geometrical deformation produced by the spatial gradient of the effective electromagnetic parameter K(r).

Although both mechanisms act in the same external environment, they are assigned different physical roles and are therefore examined separately.

8.2. Direct Gravitational Deflection of EM-Wave Momentum

Section 7 established that the proposed electromagnetic structure possesses an effective inertial mass associated with its kinetic energy:

$$m_i = W_k/c^2$$

Part A4 further assumes equality between inertial and gravitational mass:

$$m_g = m_i$$

The gravitational force exerted by the Sun is therefore

$$F_g = GM_\odot m_i/r^2$$

The component perpendicular to the initial propagation direction changes the direction of the wave momentum.

For the approximately straight reference trajectory, its magnitude is

$$F_{g,\perp} = GM_\odot m_i b/r^3$$

The resulting change in transverse momentum is obtained by integrating the force along the trajectory.

In the leading weak-field approximation, the electromagnetic structure obeys the momentum relation

$$p = m_i c$$

Using the corresponding reference propagation parameter in the trajectory integration, the angular deflection becomes

$$\theta_{\text{grav}} = \frac{GM_\odot b}{c^2}\int_{-\infty}^{+\infty}\frac{dx}{(x^2+b^2)^{3/2}}$$

The integral evaluates to

$$\int_{-\infty}^{+\infty}\frac{dx}{(x^2+b^2)^{3/2}} = \frac{2}{b^2}$$

Consequently,

$$\theta_{\text{grav}} = \frac{2GM_{\odot}}{bc^2}$$

This result represents the direct gravitational contribution to the deflection of the electromagnetic structure.

Its physical origin is the gravitational force acting on the wave momentum.

The same interaction can perform work and change the wave kinetic energy, as examined in Section 7. However, the change in propagation direction is specifically associated with the transverse component of the force.

The leading angular result is independent of the absolute magnitude of the electromagnetic-wave energy because both the gravitational force and the momentum are proportional to its effective inertial mass.

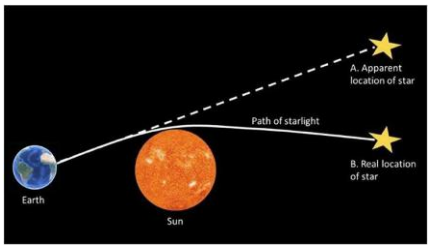

Figure 2 - *Light passing near the Sun follows a curved trajectory, producing an apparent displacement of the observed star. The proposed model attributes this deflection to the combined effects of direct gravitational interaction with electromagnetic-wave inertia and geometrical deformation of the propagation path.*

8.3. Geometrical Deflection Due to the Gradient of K

Section 6 introduced a separate geometrical mechanism.

The external scalar-field environment is represented through the effective electromagnetic parameter

$$K(r) = 1 + \alpha GM_{\odot}/(rc^2)$$

where α is a phenomenological coupling coefficient.

The geometrical propagation parameter is defined as

$$n(r) = \sqrt{K(r)}$$

Unlike the direct gravitational mechanism, this description does not introduce a force acting on the wave's inertial mass.

Instead, the spatial variation of K produces different geometrical propagation conditions across the transverse extent of the electromagnetic structure.

The side closer to the Sun is exposed to a stronger external influence than the opposite side. This asymmetry produces a gradual rotation of the wavefront and a corresponding change in the direction of propagation.

For weak fields,

$$n(r) \approx 1 + \alpha GM_{\odot}/(2rc^2)$$

The geometrical-optics relation introduced in Section 6 expresses the local curvature through the transverse gradient of n.

For the nearly straight solar trajectory, the magnitude of the transverse gradient is

$$|\partial n/\,\partial y| \approx \alpha GM_{\odot} b/(2c^2 r^3)$$

The accumulated geometrical deflection is therefore

$$\theta_{\text{geom}} = \frac{\alpha GM_{\odot} b}{2c^2} \int_{-\infty}^{+\infty} \frac{dx}{(x^2 + b^2)^{3/2}}$$

Using the same geometrical integral gives

$$\theta_{\text{geom}} = \alpha GM_{\odot}/(bc^2)$$

This expression represents the geometrical contribution to solar light deflection.

Its origin is the transverse variation of the external electromagnetic propagation conditions, not the gravitational work performed on the electromagnetic structure.

The geometrical contribution is independent of the absolute kinetic energy in the present approximation.

8.4. Physical Distinction Between the Two Mechanisms

The two deflection mechanisms lead to similar mathematical dependencies, but their proposed physical origins are different.

The direct gravitational mechanism acts on the inertia and momentum of the propagating electromagnetic structure.

It is accompanied by gravitational energy exchange. During approach toward the Sun, the wave gains kinetic energy; during departure, the gained energy is returned through work against the gravitational attraction.

The geometrical mechanism acts through the spatial variation of the effective parameter K.

Its transverse gradient changes the orientation of the electromagnetic wavefront and thereby the propagation direction.

In the stationary, nondissipative approximation, this geometrical mechanism is treated as producing no direct change in the wave kinetic energy.

The distinction can be summarized as follows.

Property	**Direct gravitational mechanism**	**Geometrical mechanism**
Physical origin	Gravitational interaction with wave inertia	Spatial gradient of K
Primary action	Change of momentum	Rotation of the wavefront
Energy exchange	Gravitational work	No direct work
Structural consequence	Change in kinetic energy and effective volume	Geometrical deformation

Angular contribution	Gravitational deflection	Geometrical deflection

The mechanisms are therefore distinguished by their physical action rather than by the mathematical form of their resulting angular contributions.

The present model treats them as separate contributions in the weak-field approximation. A complete dynamical theory would be required to establish their independence beyond this approximation.

8.5. First-Order Combination of Deflection Contributions

The proposed model distinguishes two physical mechanisms contributing to solar light deflection. The first is the direct gravitational interaction with the inertia and momentum of the electromagnetic wave. The second is the geometrical deformation of the wavefront caused by the spatial gradient of the effective electromagnetic parameter K.

Since both angular contributions are small in the solar gravitational field, their effects are combined in the first-order approximation:

$$\theta_{\text{total}} = \theta_{\text{grav}} + \theta_{\text{geom}}$$

The direct gravitational contribution was derived independently from the gravitational force acting on the propagating electromagnetic structure:

$$\theta_{\text{grav}} = \frac{2GM_{\odot}}{bc^2}$$

The geometrical contribution depends on the phenomenological coefficient α:

$$\theta_{\text{geom}} = \frac{\alpha GM_{\odot}}{bc^2}$$

Consequently, the total deflection becomes

$$\theta_{\text{total}} = \frac{(2+\alpha)GM_{\odot}}{bc^2}$$

The coefficient α is not assumed in advance. Its value is determined empirically from

astronomical measurements of solar light deflection.

8.6. Empirical Determination Using the Modern Eddington Experiment 2024

During the total solar eclipse of April 8, 2024, the Modern Eddington Experiment 2024 MEE2024 obtained astronomical images of stars near the Sun. The experiment used modern digital imaging and astrometric analysis to determine the apparent displacement of stellar positions.

The published analysis of 171 stars yielded a solar-limb deflection coefficient of

$$\theta_{\text{obs}} = (1.84 \pm 0.24),\text{arcsec}$$

The reported value was obtained by fitting the observed stellar displacements to an inverse-distance dependence. It therefore represents an experimentally estimated angular coefficient rather than an individual stellar displacement measured directly at the solar limb.

For the solar gravitational field, the direct gravitational contribution predicted by the present model is

$$\theta_{\text{grav}} = 0.8756,\text{arcsec}$$

The remaining contribution attributed to the geometrical mechanism is therefore

$$\theta_{\text{geom}} = 1.84 - 0.8756 = 0.9644,\text{arcsec}$$

The geometrical coefficient follows from

$$\alpha = \frac{(\theta_{\text{obs}} - \theta_{\text{grav}})R_{\odot}c^2}{GM_{\odot}}$$

Using the solar gravitational angular factor

$$\frac{GM_{\odot}}{R_{\odot}c^2} = 0.4378,\text{arcsec}$$

gives

$$\alpha = 2.20$$

The uncertainty propagated from the reported angular measurement is

$$\Delta\alpha = \frac{0.24}{0.4378} = 0.55$$

Thus, the empirical result is

$$\alpha = 2.20 \pm 0.55$$

The corresponding effective electromagnetic parameter becomes

$$K(r) = 1 + 2.20\frac{GM_{\odot}}{rc^2}$$

At the solar surface, this gives

$$K(R_{\odot}) = 1.00000468$$

The uncertainty associated with the fitted coefficient corresponds to approximately 1.17 parts per million in K at the solar surface. [9],[10]

8.7. Interpretation of the Two Contributions

The empirical calibration gives a geometrical deflection of approximately 0.964 arcseconds, compared with the independently calculated direct gravitational contribution of approximately 0.876 arcseconds.

The central values are therefore not identical. Their approximate equality is an observational consequence of the fitted coefficient and is not imposed as a theoretical condition.

The two mechanisms retain their distinct physical interpretations. The direct gravitational contribution arises from the action of gravitational force on electromagnetic-wave momentum, while the geometrical contribution arises from the spatially varying external electromagnetic conditions.

The MEE2024 measurement constrains their combined angular effect. It does not independently establish the existence or magnitude of each mechanism.

Furthermore, the experimental uncertainty permits a range of values for the geometrical coefficient. The result should therefore be interpreted as a phenomenological calibration of the proposed model, rather than as a

complete derivation of the nonlinear electromagnetic response.

The resulting formulation connects the observed solar light deflection with two distinct physical mechanisms while leaving the microscopic origin of the geometrical coupling coefficient for future investigation.

8.8. Deflection at Different Solar Distances

The two mechanisms of solar light deflection have the similar inverse-distance dependence in the weak-field approximation, although their proposed physical origins are different.

The direct gravitational contribution is determined by the interaction between the solar gravitational field and the inertia of the electromagnetic wave:

$$\theta_{\mathrm{grav}}(b) = \frac{2GM_{\odot}}{bc^2}$$

The geometrical contribution is determined by the spatial gradient of the effective electromagnetic parameter K:

$$\theta_{\mathrm{geom}}(b) = \frac{\alpha GM_{\odot}}{bc^2}$$

Using the coefficient derived from the Modern Eddington Experiment 2024,

$$\alpha = 2.20 \pm 0.55$$

the combined deflection is

$$\theta_{\mathrm{total}}(b) = \frac{(2+\alpha)GM_{\odot}}{bc^2}$$

For the central empirical value of the coefficient, this becomes

$$\theta_{\mathrm{total}}(b) = \frac{4.20GM_{\odot}}{bc^2}$$

The solar gravitational angular factor at the solar surface is

$$\frac{GM_{\odot}}{R_{\odot}c^2} = 0.4378,\mathrm{arcsec}$$

Therefore, at the solar limb, the predicted contributions are

$$\theta_{\mathrm{grav}} = 0.8756,\mathrm{arcsec}$$

$$\theta_{\mathrm{geom}} = 0.9632,\mathrm{arcsec}$$

and their sum is

$$\theta_{\mathrm{total}} = (1.839 \pm 0.241),\mathrm{arcsec}$$

The following table presents the calculated angular deflections at different minimum distances from the solar center.

Distance $b/R_{\odot}$	Gravit.	Geomet.	Total
1.0	0.876″	0.963″	1.839″ ± 0.241″
1.5	0.584″	0.642″	1.226″ ± 0.161″
2.0	0.438″	0.482″	0.919″ ± 0.120″
3.0	0.292″	0.321″	0.613″ ± 0.080″
5.0	0.175″	0.193″	0.368″ ± 0.048″
10.0	0.0876″	0.0963″	0.183″ ± 0.024″
20.0	0.0438″	0.0482″	0.0919″ ± 0.012″
50.0	0.0175″	0.0193″	0.036″ ± 0.0048″

Table 1. Solar light deflection at different distances, using the empirical coefficient from MEE2024. *The gravitational contribution is calculated from the proposed wave inertia, while the geometrical contribution uses the coefficient determined from MEE2024. The indicated uncertainties are propagated from the experimental uncertainty in α.*

Both angular contributions decrease in proportion to the inverse of the minimum distance from the Sun.

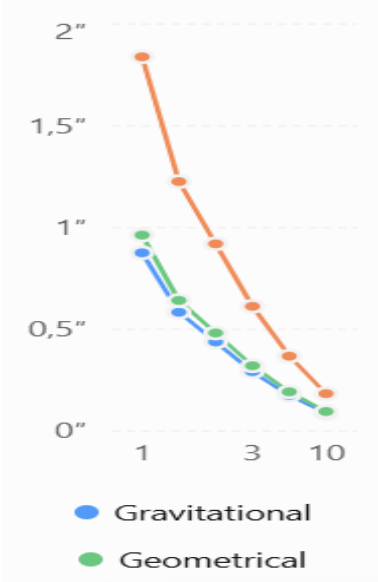

Figure 3 - *Calculated gravitational, geometrical, and total angular deflections as functions of the minimum distance from the Sun, using α = 2.20. Both contributions decrease approximately inversely with distance. Their sum reproduces the empirically calibrated solar-limb deflection.*

The geometrical contribution is slightly larger than the gravitational contribution when the central empirical coefficient is used. However, the uncertainty of the geometrical coefficient does not establish a statistically significant difference between their magnitudes.

An important consequence is that both mechanisms produce the same leading spatial dependence. Measurements of the total deflection at different solar distances can therefore test the predicted inverse-distance behavior, but cannot independently determine how much of the deflection originates from each mechanism.

The numerical results illustrate the compatibility of the proposed combined model with the empirical solar-limb deflection. They do not constitute an independent prediction of the overall coefficient, since the geometrical contribution has been calibrated using the observed angular displacement.

A more decisive test of the two-mechanism interpretation would require an independent determination of the effective electromagnetic parameter K or another observable capable of distinguishing geometrical deformation from direct gravitational momentum transfer.

8.9. Conditions and Limits of the Weak-Field Model

The preceding analysis describes solar light deflection as the combined result of two physically distinct mechanisms: direct gravitational interaction with the inertia of an electromagnetic wave and geometrical deformation caused by spatial variations in the effective electromagnetic properties of the surrounding field.

The direct gravitational contribution is obtained by integrating the transverse gravitational force along the wave trajectory. Its leading-order magnitude follows from the proposed equivalence between the inertial and gravitational masses of the electromagnetic structure.

The geometrical contribution is derived from the spatial gradient of the parameter K. Its magnitude depends on the coupling coefficient α, which is determined empirically rather than derived from the microscopic electromagnetic structure.

Using the Modern Eddington Experiment 2024, the present analysis obtains

$$\alpha = 2.20 \pm 0.55$$

The corresponding geometrical contribution is slightly larger than the direct gravitational contribution at the central fitted value. However, their difference is not statistically significant within the experimental uncertainty.

The calculation relies on the weak-field approximation, an approximately spherical solar gravitational field, small angular deflections, and a stable electromagnetic structure throughout the passage. Contributions of higher order and possible

nonlinear coupling between the two mechanisms are neglected.

An important limitation is that both contributions have the same leading inverse-distance dependence. Consequently, measurements of the total angular deflection alone cannot uniquely distinguish between them.

The empirical determination of α therefore establishes compatibility between the proposed combined model and the selected astronomical observation, but does not independently confirm the physical existence of both mechanisms.

A stronger test would require an independent calculation or measurement of K, derived from the external scalar fields introduced in Part A4, or an observable capable of separating gravitational momentum transfer from geometrical wavefront deformation.

Within these limitations, the proposed framework provides a consistent first-order description of solar light deflection in terms of electromagnetic-wave inertia and spatially varying propagation geometry. It also identifies the physical quantities that must be determined independently to develop the model beyond its present phenomenological formulation. [5], [6], [7], [8]

9. Quantitative Results and Experimental Implications

9.1. Overview of the Quantitative Model

The preceding sections developed a description of electromagnetic-wave interaction with external gravitational and electromagnetic fields. The analysis distinguishes between the kinetic energy and inertia of the propagating electromagnetic structure and the geometrical response of its wavefront to spatially varying external conditions.

Three quantitative consequences are particularly relevant.

First, gravitational interaction changes the kinetic energy and effective inertial mass of an electromagnetic wave during its passage through a gravitational field.

Second, the associated energy variation produces a structural response, which can be expressed through the dimensions of the coherent electromagnetic-wave chain.

Third, solar light deflection is described as the first-order combination of direct gravitational momentum transfer and geometrical wavefront deformation.

These effects are examined below using the solar gravitational field as a reference environment.

9.2. Gravitational Variation of Wave Energy and Inertia

Section 7 introduced the relation between electromagnetic-wave kinetic energy and effective inertial mass:

$$m_i = \frac{W_k}{c^2}$$

Assuming equality between inertial and gravitational mass, gravitational work produces the following radial dependence of the wave energy:

$$W_k(r) = W_{k,\infty} \exp\left(\frac{GM_\odot}{rc^2}\right)$$

The corresponding inertial mass varies proportionally:

$$m_i(r) = m_{i,\infty} \exp\left(\frac{GM_\odot}{rc^2}\right)$$

For the solar gravitational field, the dimensionless parameter at the solar surface is

$$q_\odot = \frac{GM_\odot}{R_\odot c^2} = 2.123 \times 10^{-6}$$

Consequently, the relative change in kinetic energy near the solar surface is

$$\frac{\Delta W_k}{W_{k,\infty}} \approx 2.123 \times 10^{-6}$$

The corresponding relative change in inertial mass is

$$\frac{\Delta m_i}{m_{i,\infty}} \approx 2.123 \times 10^{-6}$$

Thus, the proposed model predicts an increase of approximately 2.12 parts per million in both quantities at the solar surface relative to their values far from the Sun.

The magnitude of this change is independent of the initial wave energy in the present approximation.

During departure from the Sun, the gravitational interaction reverses the energy exchange. The wave consequently recovers its original kinetic energy and effective inertial mass at a sufficiently large distance.

The calculation represents a conservative gravitational exchange and does not imply permanent energy loss or gain during an ideal solar passage.

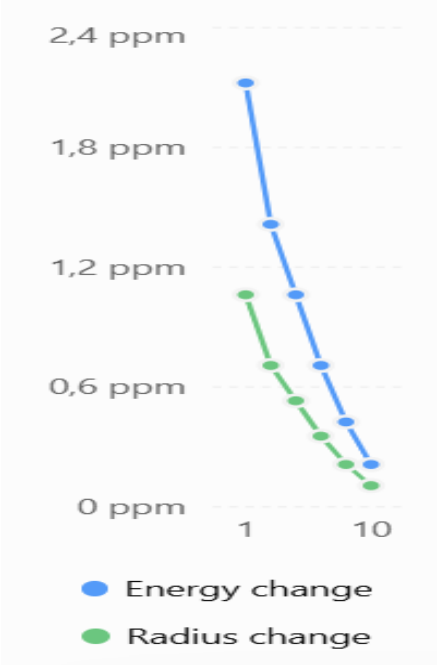

Figure 4 - *Relative changes in electromagnetic-wave kinetic energy and transverse radius with distance from the Sun. The radius variation assumes an approximately constant coherent-chain length and saturated energy density. Both effects decrease with increasing distance from the gravitational source.*

9.3. Structural Response of the Coherent EM-Wave Chain

The energy variation described above is accompanied by a geometrical response of the electromagnetic structure.

The structural approximation developed in Part B2 relates the wave energy to its transverse dimensions and coherent chain length:

$$W_k = C_u u_s R^2 L$$

Here, R represents the characteristic transverse radius, L the coherent chain length, u_s the characteristic saturated electromagnetic energy density, and C_u a dimensionless geometrical factor.

If the saturated energy density and geometrical factor remain approximately constant, the structural relation becomes

$$R^2 L \propto W_k$$

Combining this expression with the gravitational energy relation gives

$$\frac{R^2(r)L(r)}{R_\infty^2 L_\infty} = \exp\left(\frac{GM_\odot}{rc^2}\right)$$

At the solar surface, the corresponding relative increase in the structural volume factor is approximately

$$\frac{\Delta(R^2 L)}{R_\infty^2 L_\infty} \approx 2.123 \times 10^{-6}$$

The separate changes in transverse radius and chain length are not uniquely determined by this equation.

As an illustrative limiting case, consider a coherent chain whose length remains approximately constant during the gravitational interaction.

The transverse radius then varies according to

$$R(r) = R_\infty \exp\left(\frac{GM_\odot}{2rc^2}\right)$$

At the solar surface, the relative radius increase is approximately

$$\frac{\Delta R}{R_\infty} \approx 1.0615 \times 10^{-6}$$

This corresponds to an expansion of about 1.06 parts per million.

This numerical estimate is conditional on the assumed constant chain length and saturated energy density. A different structural response could redistribute the energy variation between transverse expansion and longitudinal deformation.

The combined relation for R^2L is therefore more general within the proposed structural approximation than the individual estimate for R.

9.4. Empirical Geometrical Coupling Near the Sun

The geometrical mechanism is represented by the effective electromagnetic parameter

$$K(r) = 1 + \alpha\frac{GM_\odot}{rc^2}$$

Section 8.6 used the Modern Eddington Experiment 2024 to determine the coefficient α.

The published solar-limb deflection coefficient was

$$\theta_{\text{obs}} = (1.84 \pm 0.24),\text{arcsec}$$

The direct gravitational contribution calculated in the proposed model is

$$\theta_{\text{grav}} = 0.8756,\text{arcsec}$$

The remaining angular contribution was attributed to geometrical wavefront deformation, giving

$$\alpha = 2.20 \pm 0.55$$

The corresponding effective parameter at the solar surface is

$$K(R_\odot) = 1.00000468 \pm 0.00000117$$

Thus, the central empirical estimate corresponds to a relative increase of approximately 4.68 parts per million in the effective electromagnetic product.

Using the definition introduced in Section 5,

$$K(r) = \frac{\varepsilon_{\text{eff}}(r)\mu_{\text{eff}}(r)}{\varepsilon_0\mu_0}$$

the product of the effective electromagnetic parameters becomes

$$\varepsilon_{\text{eff}}(r)\mu_{\text{eff}}(r) = K(r)\varepsilon_0\mu_0$$

This relation specifies the product of the two parameters but does not independently determine either one.

It is important to distinguish the empirical and theoretical elements of this result.

The observed angular deflection constrains the total effect. The division into gravitational and geometrical contributions follows from the assumptions of the proposed two-mechanism model.

The coefficient α is therefore an empirically calibrated parameter rather than an independently derived electromagnetic constant.

9.5. Comparison of the Principal Solar-Field Effects

The numerical results obtained for the solar surface are summarized in Table 2.

Quantity	Relative variation	Origin
Wave kinetic energy	+2.123 ppm	Gravitational work
Effective inertial mass	+2.123 ppm	Energy–inertia relation
Structural factor R^2L	+2.123 ppm	Conditional saturated-structure relation

Transverse radius, constant L	+1.062 ppm	Conditional structural adjustment
Effective parameter K	+4.68 ± 1.17 ppm	Empirical angular calibration

Table 2. Quantitative effects associated with the solar gravitational field. *The values refer to conditions at the solar surface relative to a distant reference region. The structural estimates depend on the stated geometric assumptions, while the value of K is obtained from the selected astronomical measurement.*

The table reveals that all predicted or inferred variations are small in the weak solar gravitational field.

Nevertheless, their physical roles differ.

The energy and inertial-mass variations arise from the assumed direct gravitational interaction.

The structural factor describes the corresponding change in the dimensions of the coherent electromagnetic structure.

The effective parameter K describes the geometrical response of the surrounding electromagnetic propagation conditions.

The comparison does not establish a direct numerical identity between these quantities. In particular, the empirical magnitude of K cannot presently be calculated from the predicted variation of wave kinetic energy.

Establishing such a relationship would require a dynamical description of the interaction between the external scalar fields and the electromagnetic structure.

9.6. Experimental Implications and Independent Tests

The model suggests several distinct experimental approaches.

Solar angular deflection. Measurements of stellar or radio-source positions near the Sun constrain the total angular response and its dependence on the minimum solar distance. Improved measurements can reduce the uncertainty in the fitted coefficient α, provided that the direct gravitational contribution assumed by the model is retained.

However, angular measurements alone cannot separate the two contributions when both have the same leading inverse-distance dependence.

Independent determination of electromagnetic field response. A more discriminating experiment would establish whether external gravitational conditions produce the effective electromagnetic variation represented by K. Such a test would need to constrain the response independently of the total solar-deflection angle.

Wave-energy and structural measurements. The proposed model relates gravitational energy exchange to changes in the effective volume and dimensions of a coherent electromagnetic structure. Measurements of the structural response under controlled external-field conditions could therefore test the assumed relation between kinetic energy and geometry.

Such measurements would require observables sensitive to the proposed transverse radius or coherent-chain structure. These quantities are not independently established by the existing solar-deflection observations.

Controlled external-field gradients. If the geometrical mechanism is governed by a more general interaction with external scalar fields, laboratory configurations with measurable field gradients may provide an alternative testing environment.

A successful test would need to distinguish geometrical propagation effects from ordinary electromagnetic refraction, material response, and instrumental influences.

The most informative experiments would be those that constrain the geometrical coefficient independently of the solar light-deflection measurements used to calibrate it.

9.7. Quantitative Status and Remaining Constraints

The numerical calculations demonstrate that the proposed electromagnetic-wave framework can be parameterized to reproduce the measured leading solar light deflection while simultaneously providing estimates for gravitational energy exchange and structural variation.

The energy and inertia relations follow mathematically from the assumptions introduced in Sections 2 and 7.

The structural predictions follow conditionally from the saturated geometrical relation developed in Part B2.

The geometrical coefficient α, however, remains empirically determined. Its microscopic connection to the independent external scalar fields introduced in Part A4 has not yet been established.

Furthermore, the existing angular measurements do not uniquely determine the physical division of the total deflection into the two proposed mechanisms.

These distinctions define the present quantitative status of the model.

The principal remaining objective is to derive the effective electromagnetic response K from the external field structure independently of astronomical deflection data.

Such a derivation would convert the geometrical contribution from a phenomenological fit into a separate quantitative prediction and would provide a more demanding experimental test of the proposed two-mechanism interpretation.

10. Discussion

10.1. Electromagnetic Waves as Physical Structures

The analysis presented in this work approaches electromagnetic radiation as a propagating physical structure characterized by its field distribution, kinetic energy, inertia, and geometrical dimensions.

Within this framework, an electromagnetic wave is not represented solely by its frequency or wavelength. Its transverse extent, energy distribution, and coherent chain length are also essential structural properties.

The distinction between positive electromagnetic energy and negative binding energy introduced in Part A provides the conceptual basis for describing the stability of the structure. Their magnitudes contribute to the inertia associated with wave propagation, while their signed balance characterizes the proposed internal binding state.

This interpretation allows energy transfer, structural deformation, and propagation dynamics to be discussed within a common physical description.

The model assigns kinetic energy to the propagating electromagnetic structure without introducing a separate energy contribution in addition to the electromagnetic field energy. The effective inertial mass represents the inertia associated with this energy.

Although this construction differs in interpretation from the conventional description of electromagnetic radiation, it provides a framework in which wave energy and structural geometry are explicitly related.

10.2. Energy Transfer and Structural Stability

The interaction of an electromagnetic wave with matter was examined through absorption, reflection, transmission, and scattering.

In this framework, energy transfer is accompanied by momentum transfer and may

also involve changes in the internal geometry of the electromagnetic structure.

A distinction was introduced between attenuation and structural collapse.

During attenuation, the propagating structure remains stable while its energy and characteristic dimensions change. During structural collapse, the electromagnetic configuration can no longer maintain a stable propagating state, and its remaining energy is transferred to the surrounding system or redistributed into other electromagnetic configurations.

The analysis does not establish a universal minimum energy or minimum transverse radius for the stability of coherent electromagnetic-wave chains.

Such a limit would require a more complete dynamical treatment of the interactions between electromagnetic fields, binding contributions, and the geometrical constraints developed in Part B2.

The present description therefore identifies possible structural outcomes without assigning a universal collapse threshold.

10.3. Gravitational Interaction with Electromagnetic-Wave Inertia

A central assumption of the model is that the kinetic energy of a propagating electromagnetic structure produces effective inertia and an associated gravitational response.

The resulting gravitational interaction changes the wave's momentum and kinetic energy during passage through an external gravitational field.

For a conservative interaction with the Sun, the wave gains kinetic energy during approach and returns this energy during departure.

The predicted relative energy change near the solar surface is approximately 2.12 parts per million.

Within the structural approximation adopted in this work, the corresponding variation of kinetic energy may produce changes in the transverse radius, coherent chain length, or both.

This establishes a connection between gravitational energy exchange and electromagnetic-wave geometry.

However, the distribution of the structural change between transverse and longitudinal dimensions is not uniquely determined by energy conservation alone.

Furthermore, the interpretation of the entire positive electromagnetic field energy as kinetic energy of propagation remains a specific assumption of the proposed model, rather than a result established independently by the present analysis.

10.4. Two Distinct Contributions to Solar Light Deflection

The solar light-deflection analysis introduces two mechanisms with different proposed physical origins.

The first mechanism is direct gravitational deflection arising from the interaction between the solar gravitational field and electromagnetic-wave inertia.

The second mechanism is geometrical deflection associated with the spatial gradient of the effective electromagnetic parameter K.

In the first case, the gravitational force changes the momentum of the propagating structure. In the second, different external conditions across the wavefront produce a gradual change in its orientation and propagation direction.

The mechanisms are therefore conceptually distinct even though their leading angular contributions have the same inverse-distance dependence.

Their effects are combined in the weak-field approximation.

The Modern Eddington Experiment 2024 provides an empirical solar-limb deflection coefficient of approximately 1.84 arcseconds, with a reported uncertainty of 0.24 arcseconds.

Using the direct gravitational contribution calculated in the present model, the remaining angular deflection gives the phenomenological geometrical coefficient

$$\alpha = 2.20 \pm 0.55$$

The central empirical value produces a geometrical contribution slightly larger than the direct gravitational contribution.

Their approximate equality is not imposed by the model and is not independently established by the measurement.

The observations constrain the combined angular deflection but do not, by themselves, demonstrate that it originates from two separate physical mechanisms.

A principal theoretical task is therefore to derive the geometrical coupling from the external scalar fields introduced in Part A4.

Such a derivation would permit the geometrical contribution to be predicted independently of solar light-deflection measurements.

10.5. Effective Electromagnetic Properties of Space

The parameter K was introduced to describe the combined effective response of the electromagnetic environment to external fields.

It is expressed through the product of effective electric permittivity and magnetic permeability:

$$K(r) = \frac{\varepsilon_{\text{eff}}(r)\mu_{\text{eff}}(r)}{\varepsilon_0 \mu_0}$$

The model does not require that these two effective quantities vary by equal amounts.

Only their product enters the present geometrical description.

Near the solar surface, the coefficient derived from the selected astronomical measurement corresponds to a relative variation of K of approximately 4.68 parts per million.

Although small, such a spatially varying response produces a finite accumulated angular effect along an extended propagation path.

At present, the effective quantities are model parameters. They have not been established as independently measured modifications of the local vacuum permittivity and permeability.

This distinction is important because the observed solar light deflection determines the total propagation effect, not the individual electromagnetic parameters.

An independent relationship between the external scalar fields and the effective electromagnetic response would considerably strengthen the proposed geometrical interpretation.

10.6. Relation to Conventional Electromagnetic and Gravitational Descriptions

The present model retains Maxwellian electromagnetic field energy and momentum transfer as essential elements of its formulation.

Its principal differences concern the structural interpretation of radiation, the proposed division between positive and binding energy, and the description of gravitational interaction through electromagnetic-wave inertia and an additional geometrical response.

In conventional general relativity, the leading solar light deflection arises from the geometry of spacetime and is described without introducing two separately measurable force and electromagnetic-permittivity contributions.

The two-mechanism description developed here is therefore an alternative physical

interpretation rather than an independent empirical demonstration of additional effects.

Agreement with the observed total solar deflection is a necessary consistency condition, but it is not sufficient to discriminate between the proposed model and an established theory that predicts the same leading angular dependence.

Discrimination requires observables for which the models provide different independently specified quantitative results.

Of particular interest are independent constraints on the electromagnetic parameter K, the proposed structural response of coherent wave chains, and the relationship between gravitational work and changes in electromagnetic-wave energy.

These questions provide a basis for further experimental and theoretical investigation.

10.7. Implications for Further Development

The results of Part B4 connect three areas of the proposed electromagnetic-wave theory.

The first concerns interaction with matter, where energy and momentum transfer may be accompanied by attenuation, geometrical deformation, or structural collapse.

The second concerns the inertia of electromagnetic waves and the resulting response to an external gravitational field.

The third concerns the geometrical influence of spatially varying external electromagnetic conditions on the propagation path.

Together, these mechanisms suggest that the behavior of electromagnetic radiation depends not only on its local field oscillations but also on its energy, structural dimensions, and surrounding field environment.

The present quantitative analysis remains limited by the absence of a complete dynamical derivation connecting the external scalar fields to the effective electromagnetic parameter K.

Another open issue is the detailed structural response of a coherent wave chain when its energy changes under gravitational or material interaction.

Resolving these questions would permit more independent predictions and provide a stronger basis for experimental comparison.

The model thus establishes a coherent set of working hypotheses and quantitative relationships while identifying the additional derivations required for a fully predictive electromagnetic description of wave interaction and gravitational deflection. [8]

11. Conclusions

This work extends the structural description of electromagnetic radiation developed in Parts B1–B3 by examining the inertia, energy transfer, structural evolution, and gravitational interaction of propagating electromagnetic waves.

The proposed framework treats an electromagnetic wave as a coherent physical structure possessing a finite transverse extent, an internal electromagnetic field distribution, and kinetic energy associated with propagation. Its inertia is related to the total positive electromagnetic field energy, while the distinction between positive and negative binding contributions provides the proposed basis for structural stability.

The analysis leads to the following principal conclusions.

First, interaction with matter involves the transfer of both energy and momentum. Absorption, reflection, transmission, and scattering are accompanied by changes in the electromagnetic structure. The model distinguishes gradual attenuation, during which the coherent structure remains stable, from structural collapse, when a stable propagating configuration can no longer be maintained.

Second, the kinetic energy of an electromagnetic wave is associated with effective inertia. Assuming equivalence between inertial and gravitational mass, the model describes gravitational interaction as a process that changes the wave's momentum, kinetic energy, and structural dimensions. During an ideal passage through the solar gravitational field, the wave gains kinetic energy on approach and returns this energy during departure.

Third, the structural relation between kinetic energy, transverse radius, and coherent chain length provides a quantitative connection between energy exchange and wave geometry. Under the assumed saturated-field conditions, an increase in kinetic energy is accompanied by an increase in the structural factor represented by the product of transverse area and chain length. The separate changes in radius and length remain dependent on the detailed structural response.

Fourth, solar light deflection is described through two physically distinct mechanisms. Direct gravitational interaction changes the momentum of the electromagnetic structure, while spatial variation of the effective electromagnetic parameter K produces geometrical deformation of the wavefront and its propagation path. Their leading angular contributions are combined in the weak-field approximation.

Fifth, the geometrical coupling coefficient is determined empirically using the Modern Eddington Experiment 2024. The reported solar-limb deflection coefficient of 1.84 ± 0.24 arcseconds gives

$$\alpha = 2.20 \pm 0.55$$

Within the proposed model, this corresponds to a geometrical contribution slightly larger than the direct gravitational contribution. The approximate equality of the two contributions is therefore not introduced as an independent theoretical assumption.

The resulting combined description is compatible with the selected solar light-deflection measurement. However, because the coefficient α is calibrated from the observed total deflection, this agreement does not independently establish the existence of both mechanisms.

A central result of the work is the identification of the effective electromagnetic response K as a quantity connecting external scalar fields with geometrical wave propagation. Deriving this response directly from the field structure introduced in Part A4 remains an important theoretical objective.

The proposed model therefore connects electromagnetic-wave structure, inertia, energy exchange, and gravitational deflection within a common conceptual framework. It provides quantitative relationships that can be examined further and identifies independent measurements of electromagnetic structural response and external-field coupling as particularly important tests.

In this sense, Part B4 completes the initial treatment of electromagnetic-wave formation, stability, interaction with matter, and propagation through external fields developed across Parts B1–B4, establishing a basis for subsequent investigations of electromagnetic radiation and its observable properties.

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