Unified Electromagnetic Theory of Matter and Light

Section D — **Structure and Dynamics of the Universe**

Part D4 – **Sun spots**

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Abstract

Sunspots exhibit a dark central umbra, a brighter filamentary penumbra, and relatively distinct optical boundaries. Conventional explanations attribute these features primarily to magnetically suppressed convection and the resulting temperature differences. This article investigates an alternative optical mechanism based on the proposed interaction between structured electromagnetic waves and nonuniform magnetic fields developed in Part D3.

Within the E–B–P electromagnetic-wave model, magnetic-field gradients are hypothesized to modify the propagation direction of light. Radiation generated within the magnetized photosphere may undergo progressive directional alignment, allowing a substantial fraction of the emerging electromagnetic waves to enter magnetically guided trajectories. Under stable conditions, captured radiation may follow magnetic loops and return to the solar surface at a different magnetic pole, thereby redistributing electromagnetic energy rather than allowing it to escape directly into space.

The model associates the darkness of the umbra with efficient magnetic capture, while the comparatively sharp umbral boundary may arise from a critical transition between guided and freely propagating radiation. Within the penumbra, partial capture, spatially varying magnetic deflection, and local radiation release may contribute to its intermediate brightness and filamentary structure. Illustrative calculations examine magnetic-loop dimensions, electromagnetic-wave curvature radii, and the dependence of capture on initial propagation angles.

The investigation establishes a conceptual framework rather than a complete quantitative reconstruction of observed sunspot brightness. The proposed electromagnetic coupling, stable magnetic guidance, and capture efficiency require independent experimental and observational verification. The resulting framework extends the magnetic-deflection hypothesis of Part D3 and provides a basis for investigating the optical influence of stellar magnetic structures, including Cepheid variables, in Part D5.

1. Introduction

Sunspots are among the most prominent manifestations of magnetic activity on the Sun. They appear as dark regions on the visible solar surface, typically consisting of a central umbra surrounded by a brighter penumbra. The penumbra frequently exhibits an intricate filamentary structure, while the boundaries between the photosphere, penumbra, and umbra can be remarkably distinct. These features provide valuable observational constraints on the physical processes taking place in strongly magnetized regions of the solar atmosphere.

Conventional models primarily explain the reduced brightness of sunspots through the influence of magnetic fields on convective energy transport and the resulting differences in atmospheric temperature and structure. These explanations are supported by extensive spectroscopic and magnetohydrodynamic investigations. Nevertheless, the close correspondence between magnetic field geometry and the visible structure of sunspots motivates an additional question: could the magnetic field also modify the observed brightness by directly influencing the propagation and directional distribution of electromagnetic radiation? [1] [3]

The present article investigates this possibility using the electromagnetic-wave deflection hypothesis developed in Part D3, Magnetic Deflection of Electromagnetic Waves. In that model, a nonuniform external magnetic field is proposed to modify the internal electromagnetic configuration of a propagating wave and, consequently, its direction of propagation. The resulting deflection depends on the spatial distribution of the magnetic field and on the orientation of the wave trajectory relative to the local magnetic gradient.

Part D4 extends this concept to electromagnetic radiation generated within a magnetic region. Unlike light entering an external magnetic field, radiation produced in the solar photosphere originates in an environment already permeated by the magnetic structure of the sunspot. During its passage through the photosphere, radiation undergoes repeated absorption, emission, and scattering interactions with matter. The article considers the possibility that these processes, together with the proposed magnetic interaction, may influence the angular distribution of radiation escaping from the photosphere.

The central hypothesis is that a sufficiently strong magnetic structure may capture and guide a substantial fraction of photospheric electromagnetic radiation along magnetic field structures. In the umbra, such a mechanism could reduce the amount of radiation reaching a distant observer. As an illustrative hypothesis, the article considers the possibility that up to approximately 90% of the locally generated outward radiation may be redirected into magnetically guided paths. This fraction is not derived from established emission or propagation laws and is introduced as a proposed condition requiring independent theoretical and experimental verification.

Captured electromagnetic radiation is hypothesized to propagate along magnetic loops connecting source and sink regions in the solar atmosphere. Radiation may be redirected toward other regions, returned toward the solar atmosphere, or released from magnetic structures under suitable conditions. This proposed transport mechanism is considered as a possible contribution to the optical appearance of the dark umbra.

Toward the penumbra, changes in magnetic field strength, orientation, and spatial gradients may reduce the effectiveness of magnetic capture and allow a greater fraction of radiation to escape toward the observer. Local variations in the magnetic structure may additionally modify the trajectories of escaping electromagnetic waves. In the proposed interpretation, such variations could contribute to the observed alternating bright and dark

filamentary patterns and their temporal changes.

The magnetic field of a sunspot would therefore act as a complex optical system involving radiation capture, guided propagation, partial release, and directional redistribution. A complete quantitative description would require a detailed propagation model incorporating the magnetic field geometry, the angular distribution of photospheric radiation, and the coupling between electromagnetic waves and the external magnetic field. The present work does not attempt to solve this complete optical problem. Instead, it establishes a conceptual framework, identifies the additional physical hypotheses, and proposes observational and experimental tests through which their validity may be assessed.

2. Magnetic Deflection and Alignment of Light

2.1. Interaction Between Light and an External Magnetic Field

Part D3 introduces a mechanism through which a nonuniform external magnetic field may modify the propagation direction of a structured electromagnetic wave. Within the proposed E–B–P framework, electromagnetic radiation is represented by a coherent tubular field configuration whose internal structure responds to asymmetric external magnetic conditions.

An external magnetic-field gradient induces an asymmetric redistribution of the internal electromagnetic fields. The resulting transverse momentum transfer is assumed to change the propagation direction of the wave toward regions of stronger magnetic field.

The proposed directional interaction is therefore governed primarily by the magnetic-field gradient rather than by the magnetic-field strength itself. A homogeneous external magnetic field does not produce a net transverse force under the assumed interaction law.

The present study extends the mechanism developed in Part D3 to the spatial scales and magnetic configurations encountered in solar active regions.

2.2. Curvature of the Electromagnetic Wave Trajectory

The local curvature of the electromagnetic wave trajectory can be expressed as

$$\frac{d\vec{t}}{ds} = \eta g(\alpha)\nabla_{\perp} u_B$$

where

$$u_B = \frac{B_{ext}^2}{2\mu_0}$$

and

- t is the unit propagation vector,
- s is the distance along the trajectory,
- η is the effective magnetic response coefficient,
- α is the angle between the propagation direction and the local magnetic field,
- g(α) describes the angular dependence of the interaction.

The transverse gradient is defined as

$$\nabla_{\perp} u_B = \nabla u_B - \vec{t}\left(\vec{t} \cdot \nabla u_B\right)$$

The local radius of curvature of the trajectory is consequently given by

$$\frac{1}{r_c} = \eta g(\alpha)|\nabla_{\perp} u_B|$$

The effective response coefficient incorporates the relationship between the interaction volume and the propagation energy of the electromagnetic wave, as discussed in Part D3.

2.3. Estimation of the Radius of Curvature

The available observational data do not yet permit an independent determination of the magnetic response coefficient. Solar magnetic structures nevertheless provide geometrical constraints on the possible magnitude of the proposed interaction.

An excessively strong interaction would cause magnetic structures to attract radiation from extensive surrounding regions. Such a mechanism could produce significant optical disturbances outside the observed boundaries of sunspots.

Conversely, an excessively weak interaction would prevent electromagnetic waves from following the curved magnetic structures associated with solar active regions.

Based on these considerations, the present study adopts a characteristic minimum radius of curvature in the range

$$r_{c,min} = 1000 - 2000\ km$$

with a representative value of

$$r_{c,min} = 1500\ km$$

These values constitute working model parameters rather than directly measured optical curvature radii.

The distance required to change the propagation direction by one degree, assuming constant local curvature, is

$$s_{1^\circ} = \frac{\pi r_c}{180}$$

Local curvature radius (km)	Propagation distance for a 1° deflection (km)
1000	17.5
1500	26.2
2000	34.9
3000	52.4

Table 1. Propagation distances required for a one-degree directional change at different local curvature radii.

The directional change becomes smaller toward the outer regions of the magnetic structure as the magnetic gradient decreases.

2.4. Alignment of Light within the Photosphere

The interaction between electromagnetic radiation and the magnetic structure may begin below the visible solar surface.

Electromagnetic waves generated within the photospheric layers initially propagate in different directions. Under the proposed magnetic interaction, waves approaching regions of stronger magnetic field undergo progressive directional changes.

Depending on their initial position and propagation direction, the waves may cross the central magnetic region, oscillate around its axis, or develop a spiral trajectory along the magnetic structure.

Part D3 introduces a possible stabilization mechanism through which transverse momentum components gradually decrease. The propagation direction consequently approaches the local direction of the magnetic field.

If this mechanism operates sufficiently efficiently within the photosphere, a substantial fraction of the emerging radiation may already be aligned within a few degrees of the local magnetic field before entering the upper magnetic structure.

This preliminary alignment considerably reduces the directional adjustment required for subsequent transport along a curved magnetic loop. Its quantitative efficiency depends on the available interaction distance, magnetic gradients, and transverse damping.

2.5. Selective Attraction of Radiation

The magnetic interaction does not necessarily capture all electromagnetic waves approaching a magnetic structure.

Waves passing through its outer regions encounter relatively weak magnetic gradients and experience only limited directional changes. Waves approaching the central region may undergo substantially greater deflection and, under suitable conditions, enter a guided propagation state.

For a smooth, approximately axisymmetric magnetic distribution, the transverse magnetic gradient vanishes on the central axis and reaches its maximum at a finite radial distance. The strongest local curvature therefore occurs within the central magnetic region rather than necessarily on the axis itself.

The distinction between freely propagating and magnetically guided radiation may arise through a dynamical capture threshold, even when the magnetic-field distribution remains spatially smooth.

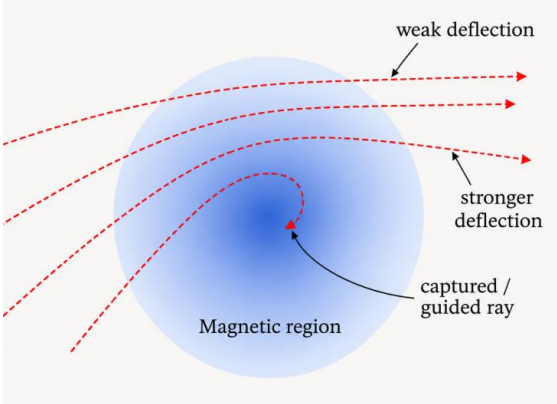


***Figure 1**. Selective magnetic deflection and capture of electromagnetic waves. Rays passing through the peripheral magnetic region undergo relatively small directional changes, while rays approaching regions of stronger magnetic gradients experience progressively greater deflection. Under suitable conditions, a wave may enter a magnetically guided trajectory. The illustration is schematic and does not represent numerically calculated trajectories.*

This selective interaction is particularly important for solar applications. Magnetic guidance must be sufficiently effective to redirect radiation originating within the umbra without producing excessive optical disturbances in the surrounding photosphere.

2.6. Transition to Magnetic Loop Guidance

The photospheric alignment mechanism provides favorable initial conditions for the subsequent transport of electromagnetic radiation along magnetic loops.

However, preliminary alignment is not necessarily a prerequisite for capture. Radiation entering a magnetic structure at larger angles may also become guided if the available transverse interaction is sufficiently strong.

The subsequent evolution depends on the curvature of the magnetic loop, the transverse magnetic-field distribution, the initial propagation direction, and the stabilization of transverse oscillations.

Once a stable guided trajectory is established, the proposed model allows radiation to follow the magnetic structure toward the opposite magnetic pole, provided that the conditions required for guidance remain satisfied throughout the loop.

Local magnetic disturbances and turbulence may interrupt this process and redirect part of the guided radiation into surrounding space.

The following chapter investigates these conditions using an illustrative three-dimensional magnetic-loop configuration.

The proposed interaction represents an extension beyond conventional linear vacuum electrodynamics. Its applicability to solar radiation must ultimately be established through quantitative trajectory calculations

and comparison with astronomical observations

3. Magnetic Guiding of Light along Solar Loops

3.1. Geometry of Solar Magnetic Loops

Solar magnetic structures extend from the photosphere into the upper layers of the solar atmosphere. Their dimensions range from relatively small magnetic loops associated with small active regions to large magnetic arches extending over considerable distances above the solar surface.

Within the proposed optical model, these structures may act as natural guides for electromagnetic radiation. Radiation entering a magnetic loop may follow its curved geometry rather than propagate freely into surrounding space.

For an initial geometrical approximation, the magnetic loop is represented by a semicircular magnetic structure with a radius of curvature R_B. Its length is approximately

$$L_B = \pi R_B$$

Three representative loop dimensions are considered.

Loop radius R_B (km)	Loop length L_B (km)
1000	3142
10,000	31,416
100,000	314,159

Table 2. Representative dimensions of semicircular solar magnetic loops.

The selected dimensions cover three orders of magnitude. The smallest loop represents a provisional lower limit for the investigation rather than an established minimum size of an umbra-producing magnetic structure.

3.2. Conditions for Magnetic Guidance

An electromagnetic wave entering a magnetic structure encounters a spatial distribution of magnetic gradients that may continuously modify its propagation direction.

For a wave to follow a curved magnetic loop, the available transverse interaction must provide sufficient trajectory curvature. A characteristic condition for guidance is

$$\kappa_{max} \geq \frac{1}{R_B}$$

or, equivalently,

$$r_{c,min} \leq R_B$$

where $r_{c,min}$ represents the minimum curvature radius attainable under the local magnetic interaction.

For approximately axial propagation, the required transverse acceleration is

$$a_{\perp} = \frac{c^2}{R_B}$$

Larger magnetic loops consequently require less trajectory curvature than smaller loops.

With the representative minimum ray curvature radius of 1500 km introduced in Chapter 2, a magnetic loop with a radius of 10,000 km provides considerable geometrical margin for guided propagation. A loop with a radius of 1000 km, by contrast, requires a stronger local interaction for the same mode of guidance.

These conditions determine whether sufficient curvature is available. They do not, by themselves, establish stable capture.

3.3. Spiral Propagation along Magnetic Structures

Radiation entering a magnetic structure generally possesses both longitudinal and transverse propagation components.

The transverse magnetic interaction redirects the electromagnetic wave toward regions of greater magnetic intensity. As the wave approaches the central magnetic region, its trajectory may cross the magnetic axis or develop oscillatory or spiral motion around it.

The internal stabilization mechanism discussed in Part D3 may gradually reduce transverse oscillations, causing the mean propagation direction to approach the direction of the magnetic structure.

In a simple local approximation, the trajectory may be represented by a helix with transverse radius r_s and longitudinal pitch p.

The angle between the propagation direction and the magnetic axis is then

$$\tan\alpha = \frac{2\pi r_s}{p}$$

The curvature radius of a helix around a straight axis is

$$r_c = \frac{r_s}{\sin^2 \alpha}$$

Consequently, the transverse radius of spiral motion is not identical to the local curvature radius of the electromagnetic wave trajectory.

As the propagation direction approaches the magnetic-field direction, the transverse radius and pitch may change. The resulting trajectory depends on the magnetic-field distribution and the stabilization dynamics of the electromagnetic wave.

The magnetic structure can therefore guide radiation without requiring exact coincidence between the wave trajectory and an individual magnetic field line.

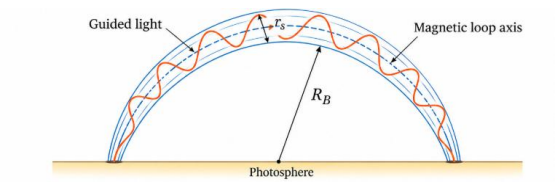


Figure 2. Schematic spiral trajectory of an electromagnetic wave guided along a solar magnetic loop. The wave follows the overall magnetic structure while undergoing transverse motion around its central axis.

3.4. Critical Threshold of Magnetic Capture

A particularly important property of magnetic guidance is the possible existence of a critical threshold separating guided and freely propagating radiation.

This threshold does not require an abrupt spatial discontinuity in the magnetic field.

Consider a smooth transverse distribution of the available ray curvature,

$$\kappa(\rho) = \frac{1}{r_{c,min}}\frac{\rho}{b}\exp\left(\frac{1}{2}\left(1-\frac{\rho^2}{b^2}\right)\right)$$

where ρ denotes the distance from the magnetic axis and b characterizes the transverse magnetic distribution.

For circular propagation in the transverse plane, the equilibrium condition is

$$\kappa(\rho)\rho = 1$$

The maximum value of the product κρ determines whether circular equilibrium trajectories can exist.

For the selected distribution, the critical condition becomes

$$r_{c,crit} = \frac{2b}{\sqrt{e}}$$

For a magnetic structure with a characteristic transverse dimension

$$b = 1250\ km$$

the critical curvature radius is

$$r_{c,crit} = 1516\ km$$

Stable and unstable equilibrium trajectories may exist below this critical value. Above it, the circular equilibrium trajectories disappear.

This example demonstrates how a smooth magnetic distribution can produce an abrupt

transition between different propagation regimes.

Such a dynamical threshold may contribute to the formation of the comparatively sharp boundary between the umbra and the penumbra. The existence of circular equilibrium trajectories, however, does not automatically establish permanent capture of incoming radiation.

3.5. Three-Dimensional Model of Magnetic Guidance

To investigate the influence of the initial propagation direction, a representative three-dimensional magnetic loop is considered.

The model parameters are:

Parameter	Assumed value
Magnetic loop radius	10,000 km
Magnetic loop length	31,416 km
Umbral diameter	5000 km
Minimum ray curvature radius	1500 km
Characteristic transverse gradient dimension	1250 km

Radiation enters the magnetic structure at different distances from its central axis and at different angles relative to the vertical direction at the photospheric entry plane.

Three representative initial propagation angles are considered: 0°, 30°, and 60°.

The case of 0° approximately represents radiation that has already undergone preliminary alignment with the nearly vertical magnetic field within the photosphere, as described in Chapter 2.

The other two cases examine the possibility of magnetic capture without such strong preliminary alignment.

3.6. Dependence of Magnetic Capture on Entry Conditions

The following table presents preliminary estimates of the fraction of radiation that may remain guided along the magnetic loop and return to the solar surface at the opposite magnetic pole.

Radial distance from the axis (km)	0°	30°	60°
0–500	100%	100%	86%
500–1000	100%	100%	31%
1000–1500	100%	94%	18%
1500–2000	100%	63%	13%
2000–2500	100%	58%	12%
2500–3000	63%	76%	28%
3000–3500	29%	93%	45%
3500–4000	8%	57%	25%

Table 3. Preliminary model estimates of the fraction of radiation returning to the solar surface through a magnetic loop for different initial radial positions and propagation angles.

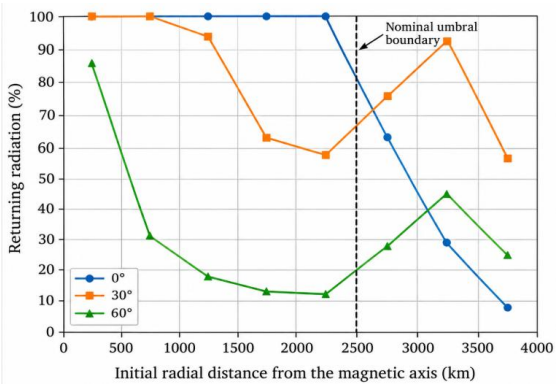


Figure 3. *Estimated fraction of radiation returning to the solar surface through a magnetic loop as a function of initial radial distance and propagation angle. The nominal umbral boundary is located 2500 km from the magnetic axis.*

The preliminary results suggest that radiation initially propagating approximately parallel to the magnetic axis may be guided efficiently throughout the central magnetic region.

Of particular interest is the considerable capture fraction at an initial propagation angle of 30°. This indicates that magnetic guidance may remain effective even when the radiation has not been completely aligned with the magnetic field before entering the loop.

At larger propagation angles, the capture efficiency generally decreases within the central region. The nonmonotonic radial distribution, however, indicates that capture also depends strongly on the complete three-dimensional trajectory.

The relatively high capture fractions outside the nominal umbral boundary for some entry angles require further investigation.

The tabulated values represent preliminary model estimates. Their numerical reproducibility must be established before they can be regarded as quantitative predictions.

3.7. Transport of Radiation along the Entire Magnetic Loop

Once radiation enters a stable guided propagation state, the proposed mechanism allows it to follow the magnetic structure along its entire length.

A gradual change in magnetic-field strength or direction does not necessarily terminate magnetic guidance, provided that sufficient transverse interaction remains available.

Radiation captured at one magnetic pole may consequently travel along the magnetic loop and return to the solar surface at the opposite magnetic pole.

Under ideal guiding conditions, the radiation remains confined to the magnetic structure and does not contribute directly to the radiation observed from Earth.

The proposed mechanism does not require the disappearance of electromagnetic energy. Instead, it redirects the energy along a different propagation path.

The return of radiation to the solar surface must therefore be included in the overall energy balance of the magnetic structure.

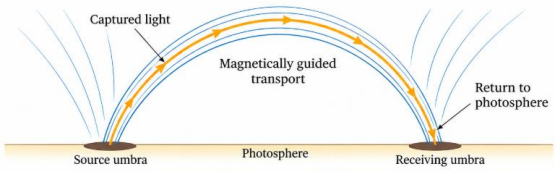


***Figure 4**. Radiation captured near one magnetic pole follows the magnetic loop and returns to the solar surface near the opposite pole. Stable magnetic guidance limits the escape of radiation into surrounding space.*

3.8. Radiation Release Associated with Magnetic Disturbances

Real solar magnetic structures are not perfectly smooth or stationary. Local disturbances, changes in magnetic-field orientation, and turbulent regions may interrupt otherwise stable magnetic guidance.

Under the proposed mechanism, such disturbances may cause part of the guided radiation to leave the magnetic structure.

The direction of the released radiation depends on the local propagation direction immediately before the disturbance and on the geometry of the disturbed magnetic region.

A stable magnetic loop may therefore remain relatively inconspicuous in visible light, whereas locally disturbed regions may become sources of escaping radiation.

This interpretation provides a possible optical contribution to localized brightness variations along solar magnetic structures. Such contributions must be distinguished observationally from radiation emitted by the plasma itself.

3.9. Implications for the Formation of the Umbra

The proposed mechanism combines two successive processes.

The first is the progressive alignment of electromagnetic radiation with the magnetic structure within the photosphere.

The second is the transport of captured radiation along the magnetic loop, potentially returning a substantial fraction of the radiation to the solar surface at the opposite pole.

The combined action of these processes may substantially reduce the amount of radiation escaping from the umbral region toward a distant observer.

Outside the central magnetic region, the weaker interaction reduces the probability of capture. The transition between stable guidance and free propagation may consequently contribute to the formation of the umbral boundary.

The present interpretation does not require an abrupt discontinuity in magnetic-field strength at that boundary. Instead, the boundary may emerge from a critical change in the propagation dynamics.

The following chapter examines how this selective transport of radiation may contribute to the observed optical structure of the umbra

4. Formation of the Umbra

4.1. Optical Origin of Umbral Darkness

The umbra is interpreted within the proposed model as a region in which a substantial fraction of the photospheric radiation becomes magnetically guided and consequently does not escape directly into surrounding space.

The mechanism involves two successive processes. Within the photosphere, magnetic gradients progressively redirect electromagnetic waves toward the local magnetic-field direction. Above the photosphere, the magnetic loop captures the previously aligned radiation and guides it toward the opposite magnetic pole.

The resulting darkness is therefore attributed to a reduction of escaping radiation rather than to its disappearance.

This interpretation introduces an optical mechanism that does not require a lower photospheric temperature or a geometrical depression as its initial causal assumptions. The existence of these phenomena, as established by solar observations, is not disputed. Their relationship to the proposed mechanism remains a subject of further investigation.

4.2. Magnetic Capture in the Central Umbral Region

The magnetic field within the umbra is predominantly aligned with the local surface normal. Radiation that has undergone preliminary magnetic alignment within the photosphere enters the magnetic loop under favorable guiding conditions.

As demonstrated by the illustrative model in Chapter 3, magnetic capture may remain effective even at initial propagation angles of approximately 30°.

A particularly important question concerns radiation originating directly on the magnetic axis. In an approximately symmetric magnetic structure, the transverse magnetic gradient vanishes on the axis.

However, the magnetic axis itself follows a curved trajectory. An electromagnetic wave initially propagating along the axis tends to continue in its original direction and consequently moves away from the curved magnetic axis.

This displacement exposes the wave to an increasing transverse magnetic gradient, which redirects it toward the central magnetic region.

The wave may subsequently oscillate around the magnetic axis or develop a spiral trajectory along the magnetic loop.

Thus, the vanishing transverse gradient on the axis does not necessarily prevent magnetic capture of radiation originating in the central part of the umbra.

4.3. Formation of the Sharp Umbral Boundary

One of the characteristic features of a developed sunspot is the comparatively sharp boundary separating the dark umbra from the brighter penumbra.

The proposed optical interpretation associates this boundary with a critical transition between magnetically guided and freely propagating radiation.

Within the central magnetic region, the available transverse interaction may be sufficient to establish stable guided propagation. Toward the outer regions, the weakening magnetic gradient reduces the ability of the magnetic structure to capture and retain radiation.

As discussed in Chapter 3, the transition between these propagation regimes may occur at a critical value even when the underlying magnetic distribution remains smooth.

Let C represent the fraction of radiation captured by the magnetic structure at a given radial position and initial propagation direction:

$$C = C(\rho, \alpha)$$

Within the umbra, the capture fraction is expected to be relatively high. Beyond the critical boundary, an increasing fraction of radiation escapes into surrounding space.

The optical boundary may therefore be considerably sharper than the underlying spatial variation of the magnetic field.

Conceptual illustration of a sharp capture transition arising from a smooth variation of magnetic guiding capacity.

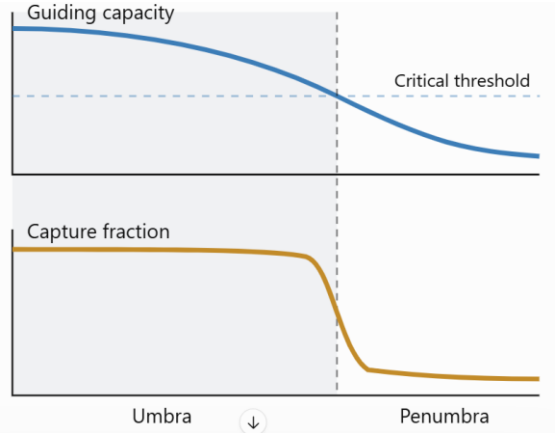


Figure 5. *Formation of an optical boundary through a critical transition between guided and freely propagating radiation. The curves illustrate the proposed mechanism rather than a measured or numerically reconstructed umbral profile.*

The observed sharpness of the umbral boundary may thus reflect a nonlinear property of electromagnetic-wave propagation rather than an abrupt discontinuity in magnetic-field strength.

4.4. Limited Capture of Radiation from the Surroundings

The magnetic structure must not capture excessive amounts of radiation originating outside the sunspot.

If the magnetic interaction were excessively strong, electromagnetic waves passing through the surrounding photosphere would undergo substantial directional changes. This could produce extensive optical disturbances beyond the observed boundaries of the sunspot.

The characteristic minimum curvature radius of 1000–2000 km introduced in Chapter 2

represents a provisional estimate intended to restrict this effect.

Electromagnetic waves approaching the central magnetic region may undergo sufficiently large directional changes to enter a guided state. Waves passing through peripheral regions generally experience weaker deflection and may continue into surrounding space.

A magnetic structure therefore does not constitute an impermeable optical barrier. Radiation may enter the magnetic region, undergo substantial deflection, and subsequently leave it. Under suitable geometrical conditions, directional changes occurring on opposite sides of the magnetic structure may partly compensate for one another.

The final propagation direction depends on the complete trajectory rather than on the initial magnetic deflection alone.

The relatively high capture fractions obtained for some oblique trajectories outside the nominal umbral boundary in Chapter 3 indicate that additional constraints on the angular dependence and spatial distribution of the interaction are required.

4.5. Reduction of Umbral Brightness

The observed brightness of the umbra depends on the amount of radiation that ultimately reaches the observer.

A simplified estimate of the fraction of radiation escaping from a selected photospheric region is

$$T(\rho, \alpha) = 1 - C(\rho, \alpha)$$

where T represents the fraction not captured by the magnetic structure.

If the capture fraction is high throughout the central magnetic region, only a small fraction of the original radiation remains available for direct escape.

The following table illustrates this relationship.

Captured fraction	Fraction remaining available for escape
50%	50%
70%	30%
80%	20%
90%	10%
95%	5%

Table 4. Illustrative relationship between magnetic capture and the fraction of radiation remaining available for escape.

The escaping fraction must not, however, be identified directly with the observed relative brightness of the umbra.

Radiation that escapes may propagate in directions other than toward the observer. Conversely, radiation originating in neighboring regions may be redirected toward the observer.

A quantitative determination of umbral brightness must therefore include the complete angular distribution of the emitted radiation and the mapping of its trajectories through the three-dimensional magnetic structure.

The capture mechanism provides a possible explanation for reduced umbral brightness, but its quantitative contribution must be established through such a calculation.

4.6. Influence of the Viewing Direction

The magnetic structure of a sunspot is three-dimensional, whereas the observed solar image represents its projection onto the plane perpendicular to the observer's line of sight.

When a sunspot is observed near the center of the solar disk, the observer's direction is approximately parallel to the predominantly vertical magnetic field within the umbra.

As the sunspot approaches the solar limb, the observer receives radiation propagating at progressively larger angles relative to the central magnetic structure.

The observed brightness and apparent boundary of the umbra may consequently depend on the viewing direction.

The angular dependence of magnetic capture introduced in Chapter 3 provides a basis for investigating this effect. Radiation propagating nearly parallel to the magnetic axis may experience different capture conditions from radiation propagating obliquely across the magnetic structure.

The resulting apparent geometry may include both ordinary geometrical projection and additional displacement caused by the proposed magnetic interaction.

Comparison of the same sunspot at different positions on the solar disk could therefore provide an observational test of the model.

Such a comparison must also account for the established geometrical Wilson depression and the viewing-angle dependence of conventional radiative transfer.

4.7. Return of Electromagnetic Energy to the Solar Surface

Radiation captured by a stable magnetic loop is not necessarily absorbed or dissipated during its propagation.

Under the proposed mechanism, a substantial fraction of the captured electromagnetic energy may remain guided throughout the magnetic loop and return to the solar surface at the opposite magnetic pole.

In an idealized stationary energy balance, the radiation entering the magnetic structure is divided into returning, escaping, and locally transferred energy:

$$P_{in} = P_{return} + P_{escape} + P_{transfer}$$

For ideal lossless magnetic guidance,

$$P_{return} = P_{in}$$

In real magnetic structures, disturbances and turbulence may interrupt the guided propagation and release part of the radiation into surrounding space.

The energy returning to the photospheric layers may be absorbed, redirected, or subsequently re-emitted. Its contribution must therefore be included in the thermal and radiative energy balance of the sunspot.

The proposed formation of the umbra is consequently interpreted as a redistribution of electromagnetic energy rather than its destruction.

4.8. Summary

The proposed optical interpretation of the umbra is based on the combined action of photospheric alignment and subsequent magnetic guidance of electromagnetic radiation.

Within the central magnetic region, radiation may become aligned with the magnetic structure and follow the magnetic loop toward the opposite magnetic pole. The amount of radiation escaping directly from the umbral region is consequently reduced.

The sharp umbral boundary may arise from a critical transition between stable magnetic guidance and freely propagating radiation, without requiring a discontinuous magnetic-field distribution.

An essential constraint is that magnetic capture must remain predominantly confined to the central magnetic region and must not produce excessive optical disturbances in the surrounding photosphere.

The effectiveness of the proposed mechanism depends on the magnetic geometry, the electromagnetic-wave curvature, the initial propagation direction, and the stabilization of transverse motion.

The following chapter extends this interpretation to the penumbra, where magnetic capture becomes incomplete and directional redistribution of radiation may produce a more complex optical structure

5. Photospheric Radiation and Initial Magnetic Alignment

5.1. Physical Conditions in the Solar Photosphere

The solar photosphere is the atmospheric region from which most of the Sun's observed visible continuum radiation emerges. It is not a sharply defined surface but a transition between optically dense layers, where electromagnetic radiation interacts frequently with matter, and increasingly transparent layers, through which radiation can escape into space. [9]

The photosphere consists predominantly of hydrogen and helium, together with smaller concentrations of other elements. At photospheric temperatures, hydrogen is largely neutral, while free electrons, ions, and negative hydrogen ions H^- play important roles in radiative interactions.

The visible continuum is strongly influenced by absorption and emission processes associated with H^-. Consequently, the radiation emerging from the photosphere results from a continuous exchange of energy between electromagnetic fields and the particles composing the plasma. [9]

Within a sunspot, these interactions occur in a concentrated magnetic structure extending from deeper solar layers through the photosphere and into the atmosphere above it.

The magnetic field is generally stronger and more nearly vertical in the central umbra. Toward the penumbra, the field becomes increasingly inclined and develops a more complex spatial structure. [2]

The magnetic environment is therefore present throughout the region in which the observed radiation is formed and transported.

The present study investigates whether, in addition to established radiative-transfer processes, the proposed magnetic interaction described in Part D3 may influence the directions in which electromagnetic waves propagate before escaping from the photosphere.

This possibility is particularly important because radiation entering the upper magnetic structure need not preserve its original emission direction.

5.2. Absorption, Re-emission, and Scattering of Light

Electromagnetic radiation propagating through the photosphere undergoes repeated interactions with atoms, ions, and free electrons.

An electromagnetic wave may be absorbed, transferring energy to matter. Subsequent radiative processes may release electromagnetic energy again, but the newly emitted radiation need not preserve the propagation direction, phase, or frequency of the absorbed wave.

Scattering processes also redistribute radiation among different directions.

Consequently, the angular distribution of radiation emerging from the photosphere is not determined by individual emission events alone. It reflects the combined effects of emission, absorption, scattering, and the optical properties of the surrounding plasma.

The magnetic field influences the motion of charged particles. Free electrons may undergo gyromotion around magnetic-field lines, while collisions continuously modify their velocities.

However, the magnetic motion of charged particles alone does not establish that the total

visible continuum is preferentially emitted parallel to the magnetic field.

The present hypothesis therefore distinguishes two possible contributions to the directional organization of radiation.

The first concerns the angular distribution established through ordinary interactions between radiation and matter.

The second concerns the proposed gradual deflection of propagating electromagnetic waves by magnetic gradients.

If the second mechanism operates during the propagation intervals between radiative interactions, it may progressively modify the directions of electromagnetic waves before they reach the upper photospheric layers.

Repeated absorption and re-emission may interrupt this directional adjustment. Thus, the resulting alignment depends on the balance between magnetic deflection and radiative interactions.

This distinction is essential: repeated radiative interactions do not automatically produce magnetic alignment, but they define the environment in which the proposed alignment mechanism would have to operate.

5.3. Angular Distribution of Emerging Radiation

Radiation escaping from an optically thick photosphere is not distributed uniformly among all directions.

Its emergent intensity depends on the direction of observation relative to the local solar surface normal. In conventional radiative-transfer theory, this angular dependence arises because different viewing directions sample different optical depths and atmospheric conditions.

The familiar solar limb-darkening effect provides an observational example of this directional dependence.

Let θ denote the angle between the propagation direction of an electromagnetic wave and the local magnetic-field direction.

The angular distribution of the escaping radiation can be represented by

$$I = I(\theta)$$

Within the central umbra, where the magnetic field is approximately vertical, θ is close to the angle between the radiation direction and the local surface normal.

The angular distribution established by ordinary radiative transfer provides the initial condition for evaluating the additional magnetic interaction.

Under the proposed E–B–P model, the magnetic gradients may progressively alter this distribution.

Radiation initially propagating at larger angles may be redirected toward the local magnetic structure, while radiation already propagating nearly parallel to the field requires smaller directional adjustments.

The resulting distribution may therefore become more concentrated around the local magnetic-field direction.

Nevertheless, the existence and magnitude of this concentration cannot be inferred from the magnetic-field geometry alone. They require a calculation of the electromagnetic-wave trajectories together with the radiative interactions occurring within the photosphere.

5.4. Progressive Magnetic Alignment within the Photosphere

The mechanism of electromagnetic-wave deflection developed in Part D3 provides a possible explanation for progressive directional alignment.

When an electromagnetic wave propagates through a region containing a transverse magnetic gradient, the proposed interaction modifies its direction of propagation.

The local directional change may be characterized by the curvature radius of the electromagnetic-wave trajectory:

$$\frac{d\alpha}{ds} = \frac{1}{r_c}$$

Here, s denotes the propagation distance and r_c the local curvature radius. The equation describes the magnitude of directional change along a locally planar trajectory; the sign depends on the direction of bending.

For approximately constant curvature, the accumulated angular deflection is

$$\Delta\alpha = \frac{L}{r_c}$$

where L is the propagation distance.

The illustrative curvature radii introduced in Chapter 2 are between 1000 and 2000 km.

For a representative value of

$$r_c = 1500\ km$$

the angular change over 100 km of uninterrupted propagation is approximately

$$\Delta\alpha = 0.0667\ rad = 3.82^\circ$$

This example demonstrates that the assumed curvature could produce directional changes of several degrees over distances comparable to characteristic photospheric length scales.

However, the result describes uninterrupted propagation through a region of approximately constant curvature. It does not represent the accumulated alignment of radiation undergoing repeated absorption and re-emission.

Moreover, a large directional deflection does not necessarily correspond to alignment with a magnetic-field line. Sustained alignment requires a stabilizing mechanism that reduces transverse motion relative to the magnetic structure.

Part D3 proposes that the internal redistribution of the E, B, and P fields may contribute to such stabilization.

If the transverse motion is progressively reduced, the propagation direction may approach the local magnetic-field direction.

Thus, electromagnetic waves emerging from the photosphere could, under sufficiently favorable magnetic conditions, already possess relatively small angular deviations from the local magnetic field.

An angular distribution concentrated within several degrees is considered a possible outcome of this mechanism, not an independently established property of photospheric radiation.

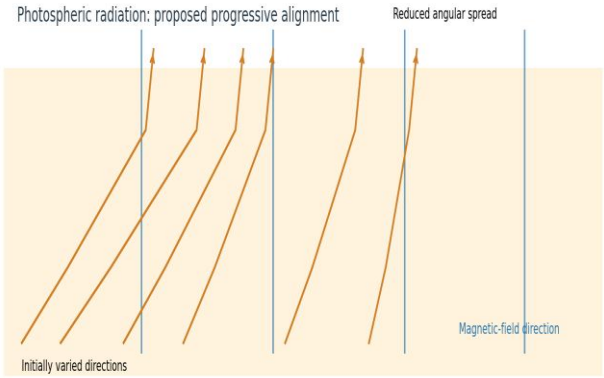


Figure 6. *Conceptual illustration of electromagnetic waves initially propagating in different directions within the photosphere. Under the proposed magnetic interaction, their propagation directions gradually approach the local magnetic-field direction before entering the overlying magnetic structure.*

5.5. Initial Alignment and Magnetic Capture Efficiency

The importance of photospheric alignment becomes apparent when considering the subsequent capture of radiation by a magnetic loop.

An electromagnetic wave already propagating nearly parallel to the local magnetic-field

direction requires relatively small corrections to enter a guided propagation state.

A wave entering the magnetic structure at a larger angle requires a stronger transverse interaction to become guided.

The illustrative calculations presented in Chapter 3 indicate that the proposed guiding mechanism may operate over a relatively broad range of initial propagation angles.

In particular, the preliminary model shows significant capture fractions even for an initial angle of approximately 30°.

This suggests that nearly perfect preliminary alignment may not be necessary for magnetic capture.

However, a narrower angular distribution emerging from the photosphere could increase the fraction of radiation entering favorable guiding conditions.

Let C(ρ,θ) represent the probability of magnetic capture for radiation emerging at radial position ρ and initial angle θ.

The total capture efficiency depends on the angular distribution of the incident radiation and the magnetic capture conditions.

A general expression is

$$\eta_{cap} = \frac{\int I(\theta) C(\rho, \theta) \cos\theta \; d\Omega}{\int I(\theta) \cos\theta \; d\Omega}$$

where the integrations extend over the outward propagation hemisphere, and $I(\theta)$ represents the angular radiative intensity at the relevant photospheric boundary.

This expression illustrates why the capture fraction cannot be determined from magnetic geometry alone.

As a working hypothesis, the present study considers the possibility that a substantial fraction of the outward radiation originating in the central umbra may enter magnetically guided propagation paths.

An illustrative upper capture fraction of approximately 90% is considered:

$$\eta_{cap} \approx 0.9$$

This value is a proposed target for numerical investigation rather than a result derived from the present equations.

The actual capture efficiency must be obtained from the combined angular radiation distribution, magnetic-field configuration, and trajectory-dependent capture probability.

The distinction between capture efficiency and observed brightness is also important. A reduction in directly escaping radiation does not necessarily produce an identical reduction in the intensity observed from Earth, because radiation may be redirected into or out of the observer's line of sight.

5.6. Connection Between Photospheric Alignment and Magnetic Loop Transport

The processes discussed in this chapter establish a possible connection between the formation of electromagnetic radiation within the photosphere and its subsequent transport along magnetic loops.

Radiation initially generated in different directions undergoes repeated interactions with matter while propagating toward the upper photospheric layers.

During the intervals of propagation, the proposed magnetic-gradient interaction may modify the wave trajectory.

Under favorable conditions, the combined evolution may produce an angular distribution in which a substantial part of the radiation propagates approximately along the local magnetic field.

Such radiation enters the upper magnetic structure with favorable initial conditions for magnetic capture.

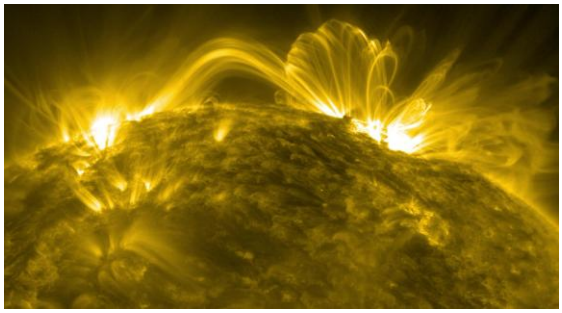


***Figure 7**. Conceptual magnetic structure above a photospheric region, illustrating the connection between initial alignment and guided transport.*

The magnetic loop may then guide part of the radiation toward the opposite magnetic pole, as described in Chapter 3.

Radiation that is not captured may escape directly or undergo additional deflection without entering a stable guided state.

The resulting distribution of electromagnetic energy is therefore determined by both the physical processes occurring within the photosphere and the propagation conditions in the overlying magnetic structure.

The principal unresolved question is whether the proposed magnetic interaction can produce sufficiently strong directional alignment during the available propagation distances, despite repeated radiative interactions.

Resolving this question requires a coupled calculation of radiative transfer and magnetic trajectory evolution.

The present chapter therefore identifies photospheric angular alignment as a potentially important contributor to magnetic capture, while retaining its quantitative efficiency as an open theoretical and observational question.

6. Stability and Release of Magnetically Guided Radiation

6.1. Stable Propagation along Magnetic Loops

Chapter 3 introduced the possibility that electromagnetic radiation captured within a solar magnetic structure may propagate along the entire magnetic loop and return to the solar surface at the opposite magnetic pole.

The proposed guiding mechanism requires a continuous transverse interaction capable of maintaining the electromagnetic-wave trajectory within the magnetic structure.

Real solar magnetic loops do not generally have constant curvature or uniform magnetic-field strength. Their geometry, inclination, and transverse magnetic gradients vary along the propagation path.

Such gradual variations do not necessarily interrupt magnetic guidance. A captured electromagnetic wave may continuously adapt its propagation direction to the changing magnetic structure.

The local guiding condition can be expressed as

$$\frac{1}{r_{c,min}(s)} \geq \frac{1}{R_B(s)}$$

where $r_{c,min}(s)$ the minimum attainable trajectory curvature radius and $R_B(s)$ is the local curvature radius of the magnetic loop.

This geometrical condition must be accompanied by sufficient transverse confinement and stability of the guided trajectory.

In the idealized model considered here, electromagnetic radiation remains confined throughout a stable magnetic loop. Its propagation does not terminate merely because the magnetic-field strength gradually decreases with height.

6.2. Transverse Oscillations and Stabilization

An electromagnetic wave entering a magnetic structure may initially propagate at an angle relative to its local magnetic axis.

The resulting transverse interaction can produce oscillatory or spiral motion around the magnetic structure, as discussed in Chapter 3.

The proposed internal E–B–P stabilization mechanism may progressively reduce these transverse oscillations.

Under suitable conditions, the wave approaches a stable guided state in which its mean propagation direction follows the magnetic loop.

The stabilization process is important because transverse confinement cannot be established solely from the instantaneous curvature of the wave trajectory.

A stable guided state must remain resistant to small variations in the transverse position and propagation direction.

If these variations remain bounded or decrease, the radiation can continue along the magnetic loop without escaping into surrounding space.

The detailed damping mechanism remains an open aspect of the proposed theory. A complete electromagnetic model must establish how transverse momentum is exchanged with the surrounding magnetic structure while maintaining energy and momentum conservation.

6.3. Magnetic Disturbances and Radiation Release

Solar magnetic structures are subject to continual disturbances caused by plasma motion, changes in magnetic stresses, and local magnetic instabilities.

These disturbances may temporarily modify the spatial distribution, orientation, or curvature of magnetic field lines.

Within the proposed optical model, a sufficiently strong local disturbance may interrupt stable magnetic guidance.

A guided electromagnetic wave may then depart from the magnetic structure and propagate into surrounding space.

The release mechanism is therefore associated primarily with local magnetic disturbances rather than with gradual changes in field strength along an otherwise stable loop.

The direction of the released radiation is determined by the electromagnetic-wave trajectory at the moment of release and by any subsequent magnetic deflection.

Radiation released at different positions along a curved magnetic loop consequently propagates in different directions.

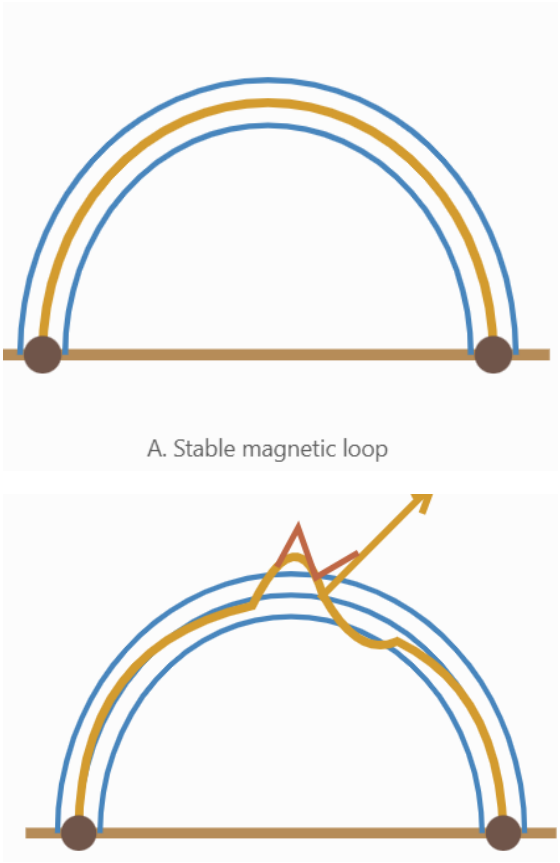


***Figure 8**. Schematic release of magnetically guided radiation caused by a local disturbance*

of the magnetic structure. Under stable conditions, the electromagnetic wave remains guided along the loop. A sufficiently strong local disturbance may interrupt confinement and permit radiation to escape into surrounding space.

This mechanism provides a possible additional source of localized optical variations associated with magnetic structures.

However, the visible and ultraviolet emission of solar magnetic loops is conventionally explained predominantly through plasma heating, excitation, and radiative processes. Observations of bright loops do not independently demonstrate the release of previously captured visible sunlight.

6.4. Energy Transport and Return to the Photosphere

Electromagnetic radiation guided along a stable magnetic loop transports energy from its original photospheric region toward another region of the solar atmosphere.

In the idealized case, the captured radiation follows the entire loop and returns to the photosphere near the opposite magnetic pole.

The receiving region may absorb part of the transported energy, redistribute it through interactions with matter, or subsequently emit electromagnetic radiation.

When guided radiation enters optically dense photospheric layers, repeated absorption, emission, and scattering may destroy its original directional organization.

The transported energy therefore need not remain directly observable as a coherent radiation stream.

The energy balance of the guided radiation can be expressed as

$$P_{guided} = P_{return} + P_{release} + P_{transfer}$$

where:

- P_{guided} is the electromagnetic power entering the magnetic loop,
- P_{return} is the power returning to the photosphere while still carried by the guided radiation,
- $P_{release}$ is the power escaping from the loop into surrounding space,
- $P_{transfer}$ is the net power transferred to matter or other degrees of freedom along the loop.

This expression assumes a stationary energy balance without net energy accumulation in the guiding structure.

For ideal guidance without intermediate release or energy transfer,

$$P_{return} = P_{guided}$$

The proposed mechanism thus redistributes electromagnetic energy spatially without requiring its disappearance.

A complete physical description must also account for the effects of returned radiation on the receiving photospheric region.

In particular, a substantial energy transfer from one magnetic pole to another could modify the local thermal and radiative balance. Such effects represent potentially important observational constraints on the model.

6.5. Observational Implications

The proposed transport and release mechanism leads to several potentially testable consequences.

A stable magnetic loop containing guided radiation need not emit substantial visible light into surrounding space. The absence of visible radiation along a magnetic structure would therefore not necessarily imply the absence of transported electromagnetic energy.

Local disturbances may cause transient radiation release. The resulting emission

direction should depend on the geometry of the magnetic loop at the release location.

Radiation released from different parts of the same loop may consequently display different apparent brightnesses for different observing directions.

If the released radiation retains measurable properties of its photospheric origin, its spectrum or polarization may differ from the radiation emitted locally by heated plasma.

The return of guided radiation to the opposite magnetic pole could also produce spatially correlated variations in the energy balance of the connected photospheric regions.

These consequences remain conditional predictions of the proposed model. Quantitative comparison with observations requires an independently specified magnetic response law and a description of radiation transport through the surrounding plasma.

6.6. Summary

The proposed magnetic-guidance mechanism distinguishes between stable transport and radiation release.

Under stable conditions, captured electromagnetic radiation follows the magnetic loop and may return to the solar photosphere at the opposite magnetic pole.

Gradual variations of magnetic-field strength and curvature do not necessarily interrupt this process, provided that the required transverse confinement remains effective.

Local magnetic disturbances may destabilize guided propagation and permit part of the radiation to escape into surrounding space.

The electromagnetic energy is thereby redistributed among guided transport, local release, and interactions with matter.

These processes provide a possible connection between the proposed optical formation of sunspot darkness and localized radiation associated with disturbed magnetic structures.

The principal unresolved questions concern the microscopic mechanism of electromagnetic-wave confinement, the stability of guided propagation, and the quantitative relationship between magnetic disturbances and radiation release.

7. Observational Characteristics and Fine Structure of the Umbra

7.1. Introduction

The preceding chapters developed a proposed optical interpretation of sunspot darkness based on the magnetic capture and guided propagation of electromagnetic radiation.

The central hypothesis is that a substantial fraction of the radiation originating within the umbra may enter magnetically guided trajectories rather than escape directly into surrounding space.

The present chapter examines how this mechanism could relate to the observed properties of the umbra, including its nonuniform brightness, small bright structures, magnetic-field organization, and appearance at different viewing angles.

The objective is not to repeat the physical mechanism developed in Chapters 2–6, but to identify observable consequences through which the proposed interpretation could be evaluated.

7.2. Nonuniform Brightness of the Umbra

Although the umbra is the darkest region of a developed sunspot, its brightness is not spatially uniform.

Observations reveal variations in continuum intensity, including relatively dark regions and localized bright structures.

Within the proposed magnetic-optical model, such variations may arise from differences in the effectiveness of magnetic capture.

The magnetic-field distribution within an umbra is not perfectly homogeneous. Local variations in field strength, inclination, transverse gradients, and magnetic curvature may influence the trajectories of electromagnetic waves.

Radiation originating in regions where magnetic guidance is particularly effective may be redirected into magnetic loops, reducing the radiation available for direct observation.

In neighboring regions with less favorable guiding conditions, a larger fraction of electromagnetic radiation may escape.

Consequently, spatial variations in magnetic capture could contribute to the observed nonuniform brightness of the umbra.

The proposed mechanism does not require a direct one-to-one correspondence between magnetic-field strength and optical darkness. Capture depends on the complete magnetic configuration, including transverse gradients, wave-entry conditions, and the stability of guided propagation.

In conventional solar physics, the nonuniform brightness of the umbra is primarily associated with variations in temperature, opacity, and magnetoconvective energy transport. The proposed optical contribution must therefore be evaluated separately from these established processes. [3] [7]

7.3. Umbral Dots and Local Magnetic Structures

High-resolution observations reveal small bright features within sunspot umbrae, commonly referred to as umbral dots. [7]

These structures are particularly interesting because they demonstrate that radiation can escape locally from regions otherwise characterized by strong magnetic fields and reduced brightness.

Within the proposed model, an umbral dot could correspond to a small region in which magnetic capture is less effective than in its surroundings.

Such a region might arise from local changes in magnetic-field inclination, transverse gradient, or the geometry of the guiding magnetic structure.

Alternatively, a localized magnetic disturbance might temporarily destabilize guided radiation and permit part of it to escape.

These two possibilities should be distinguished.

The first represents locally reduced magnetic capture of newly emerging photospheric radiation.

The second represents the release of radiation that has already entered a guided propagation state.

Both processes could increase the amount of radiation reaching a distant observer from a localized region.

However, the observed existence of umbral dots does not establish either mechanism. Their formation is conventionally understood through magnetoconvective processes involving localized transport of heat and changes in the atmospheric structure.

A useful test of the proposed optical interpretation would therefore require simultaneous measurements of umbral-dot brightness, magnetic-field geometry, plasma motion, and temporal evolution.

If magnetic guidance contributes significantly to the optical appearance of umbral dots, changes in brightness should exhibit a reproducible relationship with the magnetic conditions controlling capture or release.

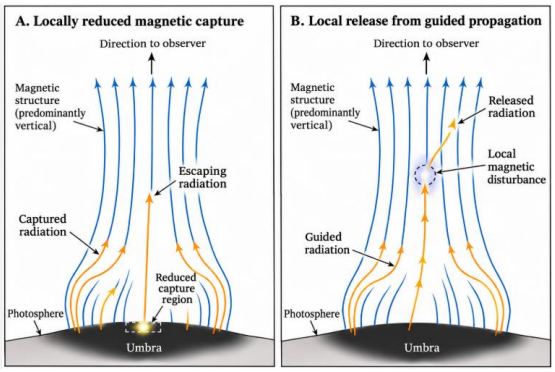


***Figure 9**. Conceptual illustration of a localized region of reduced magnetic capture within a sunspot umbra. Radiation that would otherwise enter guided propagation may escape from the disturbed region, potentially contributing to a small bright feature.*

7.4. Magnetic Structure and the Boundary of the Umbra

The umbra–penumbra boundary is closely associated with changes in the magnetic-field configuration.

Within the central umbra, the magnetic field is predominantly vertical, whereas the surrounding penumbra contains increasingly inclined and spatially complex magnetic structures.

Note on interpretation: The approximately 1867 G criterion was reported for selected stable sunspot boundaries [5]. Other observational analyses question whether this threshold is universal [6]. Accordingly, the present study treats it as an observational constraint rather than a universal physical constant.

Observational studies have identified a relatively consistent value of the vertical magnetic-field component at the boundary of stable sunspot umbrae, approximately 0.18–0.19 T in selected observational samples. [5] [6]

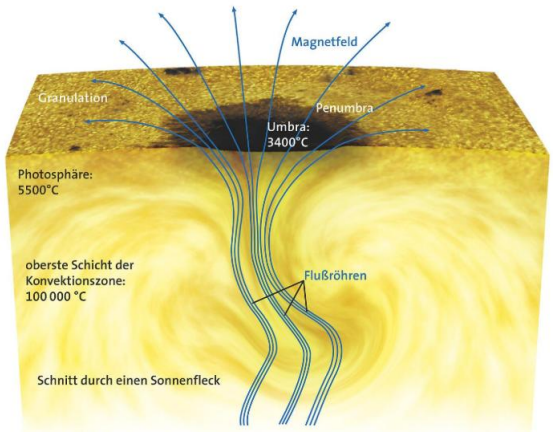


***Figure 10.** Schematic radial profiles of magnetic-field strength (blue) and relative continuum intensity (orange) across a sunspot. The illustration emphasizes the possible relationship between a smooth magnetic-field distribution and the comparatively sharp optical boundary of the umbra. The curves are conceptual and do not represent measured data.*

.

This relationship provides an important observational constraint on the proposed magnetic-optical interpretation.

As discussed in Chapter 4, the model associates the umbral boundary with a possible critical transition between predominantly guided and freely escaping radiation.

Such a transition may occur even when the underlying magnetic-field distribution changes smoothly.

However, the observed relationship between magnetic-field strength and umbral boundaries does not establish that radiation capture is responsible for the boundary.

A quantitative test would require the model to calculate the position of the transition using measured magnetic-field configurations and an independently determined electromagnetic-wave response law.

The predicted boundary could then be compared with the observed intensity boundary.

Particular attention should be given to the distinction between the magnitude of the magnetic field, its vertical component, its transverse gradient, and the curvature of the associated magnetic structure.

These quantities are related but are not interchangeable.

7.5. Influence of the Viewing Angle

The appearance of a sunspot changes as it moves across the visible solar disk.

Part of this variation results from geometrical projection, atmospheric radiative transfer, and the Wilson depression.

The proposed magnetic-optical mechanism introduces an additional possible contribution through the angular dependence of magnetic capture and radiation escape.

Radiation propagating approximately parallel to the local magnetic-field direction may encounter different guiding conditions from radiation propagating at larger angles.

Consequently, the contribution of freely escaping and magnetically redirected radiation to the observer could depend on the viewing direction.

If this mechanism is significant, sunspots observed near the center of the solar disk and near the limb may exhibit different directional brightness distributions beyond those predicted by conventional radiative-transfer effects.

The relevant quantity is not only the total fraction of magnetically captured radiation but also the complete distribution of electromagnetic-wave trajectories reaching the observer.

A useful observational approach would compare the same sunspot at different heliocentric viewing angles, using simultaneous measurements of continuum intensity and magnetic-field geometry.

The proposed mechanism would be supported only if it predicted a reproducible additional optical effect that could not be adequately explained by established geometrical and atmospheric processes.

7.6. Observational Tests of the Proposed Optical Mechanism

The proposed interpretation can be evaluated through several complementary observations.

Spatial brightness distribution. A calculated magnetic capture map should reproduce the observed radial brightness profile of the umbra, including its central darkness and transition toward the penumbra.

Fine umbral structure. Local differences in predicted magnetic capture or radiation release should be compared with the positions, brightnesses, and temporal evolution of umbral dots.

Magnetic-field geometry. The calculated optical structure should be consistent with measured magnetic-field strength, inclination, transverse gradients, and curvature.

Viewing-angle dependence. The model should reproduce the observed changes in umbral appearance at different positions on the solar disk.

Energy redistribution. If a substantial fraction of photospheric radiation is guided toward another magnetic pole, the transported energy must be included in the radiative and thermal balance of the connected regions.

These comparisons require an independently specified magnetic response law and a sufficiently realistic three-dimensional magnetic-field model.

The calculations should also account for the ordinary absorption, emission, scattering, and magnetoconvective processes responsible for the observed solar radiation.

The proposed optical contribution can then be evaluated as a distinct physical mechanism

rather than inferred from the darkness of the sunspot alone.

7.7. Summary

The umbra exhibits several observational features relevant to the proposed magnetic-guidance mechanism: reduced overall brightness, local intensity variations, bright umbral dots, a comparatively sharp boundary, and viewing-angle-dependent appearance.

Within the proposed model, these features may be influenced by spatial differences in magnetic capture, guided transport, and localized radiation release.

The interpretation does not require a uniform magnetic field or identical guiding conditions throughout the umbra.

Instead, the visible structure may reflect the combined influence of the magnetic geometry and the trajectories through which electromagnetic radiation becomes available to the observer.

The principal task is to establish whether the proposed mechanism can quantitatively reproduce these observational characteristics using independently measured magnetic-field distributions.

The following chapter extends the investigation to the penumbra, where partial magnetic capture, spatially varying deflection, and local magnetic disturbances may contribute to a more complex optical structure.

8. Optical Formation and Filamentary Structure of the Penumbra

8.1. Transition from the Umbra to the Penumbra

The penumbra represents the transition between the dark central umbra and the surrounding photosphere. Its average brightness is generally greater than that of the umbra but lower than that of the undisturbed solar surface. [1] [2]

The magnetic configuration changes considerably across this region. The predominantly vertical magnetic field of the umbra gradually transforms into a more inclined and spatially complex structure, with substantial radial components.

Within the proposed E–B–P optical model, these changes influence the conditions required for magnetic capture and guided propagation of electromagnetic radiation.

In the central umbra, a substantial fraction of photospheric radiation is hypothesized to enter magnetically guided trajectories. Toward the penumbra, the spatial distribution of magnetic gradients, field inclinations, and magnetic-loop curvature becomes less favorable for sustained guidance.

Consequently, a greater fraction of radiation may escape from the magnetic structure.

The transition need not be gradual in its optical consequences. As discussed in Chapters 3 and 4, a critical change in the conditions required for stable guidance may produce a relatively sharp transition between predominantly captured and freely escaping radiation.

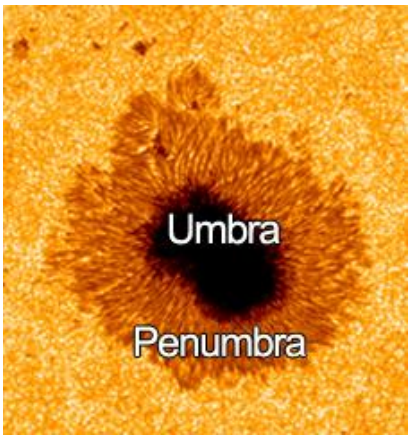


Figure 11. *Observed optical structure of a sunspot, showing the dark central umbra and the surrounding filamentary penumbra. The image illustrates the distinct brightness and structural characteristics of the two regions*

that the proposed magnetic-optical model seeks to explain.

The penumbra is therefore interpreted as a region in which magnetic capture becomes incomplete, while the remaining magnetic interaction continues to influence the directions of escaping electromagnetic waves.

This combination provides the basis for investigating the intermediate brightness and complex filamentary structure of the penumbra.

8.2. Partial Capture and Escape of Radiation

Electromagnetic radiation originating within the penumbra is generated in a magnetized photospheric environment, as is radiation originating within the umbra.

However, the propagation conditions encountered by the emerging waves are different.

Three characteristic propagation regimes may coexist.

Magnetically guided radiation. Some electromagnetic waves enter stable guided trajectories and follow the magnetic structure toward another region of the solar atmosphere.

Released radiation. Other waves initially enter guided trajectories but subsequently escape because local magnetic disturbances interrupt stable guidance.

Freely propagating radiation. A further fraction of the radiation does not become captured. These waves may nevertheless undergo substantial directional changes while crossing regions of nonuniform magnetic field.

The visible penumbra is determined by the combined contribution of radiation reaching the observer through these different propagation regimes.

A reduced capture efficiency generally increases the amount of radiation available for escape. However, the observed brightness also depends on the directions into which the escaping radiation is distributed.

Radiation may be deflected away from the observer, while radiation originating in neighboring regions may be redirected toward the same line of sight.

Consequently, the observed penumbral brightness cannot be determined solely from the fraction of magnetically captured radiation.

The proposed mechanism requires a calculation of the complete distribution of electromagnetic-wave trajectories connecting photospheric emission regions to the observer.

Within this framework, the intermediate brightness of the penumbra may arise from the combined effects of partial magnetic capture and directional redistribution of escaping radiation.

8.3. Magnetic Field Undulations and Optical Deflection

The magnetic structure within the penumbra is not perfectly smooth or stationary.

Its large-scale radial organization is accompanied by smaller variations in magnetic-field strength, inclination, curvature, and transverse gradients. [2] [8]

These variations may be represented as local undulations superimposed on the mean magnetic configuration.

They need not correspond exclusively to rapidly propagating magnetic waves. Some may represent relatively persistent structures, while others evolve with the surrounding plasma.

According to the magnetic-deflection mechanism developed in Part D3, changes in the external magnetic gradient modify the transverse interaction acting on a propagating electromagnetic wave.

The local curvature of the wave trajectory consequently depends on the magnetic conditions encountered along its path.

Neighboring electromagnetic waves may experience different curvature radii because they pass through different parts of the magnetic structure.

Even waves originating from nearby photospheric locations may therefore acquire different final propagation directions.

An important consequence is that the observed optical effect need not occur directly above the magnetic disturbance responsible for it.

A single magnetic undulation may influence numerous electromagnetic-wave trajectories. Conversely, the final direction of an individual wave may depend on several magnetic disturbances encountered along its path.

The optical response is therefore nonlocal in the geometrical sense: the entire propagation trajectory contributes to the observed distribution of radiation.

This property is particularly relevant to the formation of penumbral filaments.

8.4. Formation of Bright and Dark Penumbral Filaments

One of the most characteristic features of the penumbra is its approximately radial arrangement of elongated bright and dark filaments. [2] [8]

Within the proposed optical model, these structures may arise from local differences in the trajectories of electromagnetic waves passing through the spatially varying magnetic field.

A useful geometrical analogy is provided by the illumination patterns observed beneath gently rippled water.

When light passes through an undulating water surface, neighboring rays may converge or diverge. Their redistribution produces alternating regions of enhanced and reduced illumination.

The resulting optical pattern does not directly reproduce the geometry of the water surface. A single disturbance may produce several bright or dark regions, while multiple disturbances may contribute to one observed structure.

The proposed magnetic-optical mechanism is analogous in its geometrical complexity, although the physical interaction is different.

Instead of refraction at a material interface, the present model assumes that electromagnetic-wave trajectories respond to spatial variations in the external magnetic field.

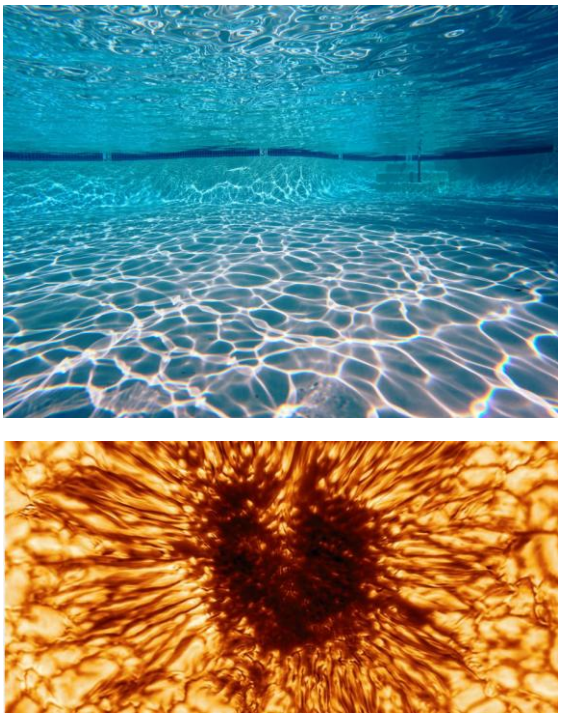


***Figure 12**. Conceptual formation of bright and dark penumbral filaments through spatially varying magnetic deflection. Local magnetic undulations modify neighboring electromagnetic-wave trajectories, potentially changing the radiation reaching the observer. The visible optical pattern need not reproduce the underlying magnetic structure directly.*

The predominantly radial organization of the penumbral magnetic field may provide a

common orientation for the resulting elongated optical features.

Local differences in magnetic gradients may cause neighboring radiation bundles to follow different trajectories.

Within the hypothesis, a bright filament may correspond to a region where magnetic capture is weaker or where the escaping radiation becomes more accessible to the observer.

A dark filament may correspond to stronger magnetic capture, reduced escape, or directional redistribution away from the observer.

These processes may occur simultaneously.

However, geometrical convergence and divergence of rays do not automatically establish the observed brightness contrast.

In particular, purely lossless redirection of radiation from an extended source of uniform radiance does not necessarily produce variations in observed surface brightness.

The proposed mechanism must therefore account for the spatial and angular distribution of photospheric radiation, the capture and release of electromagnetic waves, and the complete mapping between emitting regions and the observer.

The analogy with water waves illustrates the possible complexity of optical patterns, but does not independently establish the origin or magnitude of penumbral brightness variations.

The present interpretation consequently identifies magnetic capture and spatially varying deflection as possible additional contributions to filament formation, rather than as an already demonstrated replacement for conventional magnetoconvective explanations.

8.5. Temporal Evolution of Penumbral Filaments

The filamentary structure of the penumbra evolves over time.

Individual bright and dark features may change their positions, lengths, shapes, and intensities.

These variations are associated with changes in plasma motion, magnetic-field geometry, and local thermodynamic conditions.

Within the proposed optical interpretation, part of the observed evolution may additionally result from changes in the trajectories of electromagnetic waves.

A displacement of a magnetic disturbance, a change in its amplitude, or a variation in local field curvature may modify the directional distribution of escaping radiation.

Consequently, the apparent motion of an optical filament would not necessarily require an equivalent displacement of the material region from which the observed radiation originates.

Three different processes must therefore be distinguished:

1. Physical motion of photospheric plasma.
2. Evolution of the magnetic-field structure.
3. Apparent displacement of optical features caused by changes in radiation trajectories.

These processes may occur simultaneously but need not produce identical spatial or temporal patterns.

The proposed optical contribution could be investigated by comparing high-resolution, time-resolved continuum images with simultaneous measurements of magnetic-field strength, inclination, gradients, and plasma velocities.

A significant optical contribution would require a reproducible relationship between magnetic-structure changes and the observed filamentary brightness variations that cannot be adequately explained by established radiative-transfer and magnetoconvective processes.

8.6. The Outer Boundary of the Penumbra

The outer penumbral boundary separates the filamentary region of the sunspot from the surrounding photosphere. [2]

Within the proposed optical model, this boundary has a different physical interpretation from the inner umbra–penumbra boundary.

The inner boundary is associated with the transition from predominantly magnetically guided radiation to a regime in which a significant fraction of electromagnetic waves can escape.

The outer boundary is associated with the progressive disappearance of appreciable magnetic deflection.

Toward the outer regions of the penumbra, the transverse magnetic gradients and the conditions favoring magnetic capture generally become less effective.

The characteristic curvature radius of freely propagating electromagnetic waves consequently increases.

As the magnetic interaction becomes sufficiently weak, the electromagnetic-wave trajectory approaches a straight line.

The radiation then propagates approximately as it would in the absence of the proposed magnetic interaction.

The magnetic field itself need not vanish at the visible outer boundary.

Instead, its influence on the observer-directed radiation may become too weak to produce a distinguishable optical pattern.

A comparatively sharp outer boundary could arise if the optical consequences of magnetic deflection fall below a critical level over a relatively narrow spatial interval.

However, the existence of such an optical threshold must be demonstrated by quantitative trajectory calculations. It does not follow automatically from the smooth reduction of magnetic-field strength.

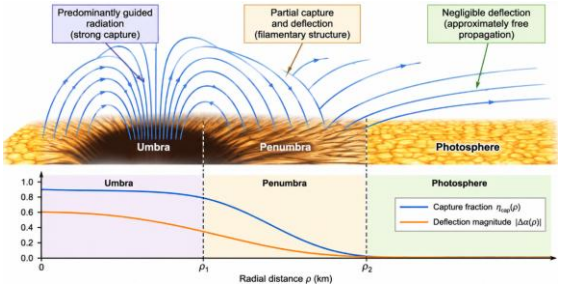


***Figure 13**. Conceptual distinction between the two penumbral boundaries. The inner boundary separates predominantly guided radiation from partial escape, whereas the outer boundary marks the transition from magnetically influenced propagation to approximately free propagation.*

The proposed interpretation therefore assigns different optical roles to the two penumbral boundaries.

The inner boundary is governed primarily by the conditions required for stable magnetic capture.

The outer boundary is governed primarily by the decreasing influence of magnetic gradients on freely propagating electromagnetic waves.

Between these boundaries, partial capture, radiation release, and spatially variable deflection may coexist.

8.7. Summary

The proposed optical interpretation of the penumbra combines incomplete magnetic

capture with the directional redistribution of escaping electromagnetic radiation.

Toward the outer regions of a sunspot, changes in magnetic-field geometry reduce the effectiveness of stable guidance, allowing a greater fraction of photospheric radiation to escape.

The remaining magnetic interaction may nevertheless modify the trajectories of freely propagating electromagnetic waves.

Local variations in magnetic gradients may produce different directional changes in neighboring radiation paths, potentially contributing to the elongated bright and dark structures characteristic of penumbral filaments.

Temporal changes in the magnetic configuration may additionally modify the apparent positions and brightnesses of these optical features.

The inner and outer penumbral boundaries are assigned different roles: the inner boundary corresponds to the proposed transition from efficient capture to partial escape, while the outer boundary corresponds to the diminishing optical influence of magnetic deflection.

The quantitative importance of these effects remains to be established through three-dimensional trajectory calculations and comparison with observations.

The following chapter considers the complete sunspot magnetic structure as a complex optical system in which multiple propagation paths, magnetic capture, radiation release, and viewing direction jointly determine the observed image.

9. The Sunspot Magnetic Field as a Complex Optical System

9.1. Multiple Deflection Paths and Magnetic Field Geometry

Within the proposed electromagnetic-wave model, the magnetic structure of a sunspot may be regarded as a complex optical system.

Unlike a conventional optical lens, whose interaction with light is primarily associated with a defined refractive geometry, the proposed magnetic interaction is distributed throughout an extended three-dimensional region.

The radius of curvature of an electromagnetic-wave trajectory may vary continuously as the wave propagates through regions of different magnetic-field strengths, gradients, and orientations.

The curvature may also change direction along the trajectory. Consequently, a wave may encounter successive regions of concave and convex bending before escaping from the magnetic structure.

Two electromagnetic waves originating from neighboring photospheric regions may therefore undergo substantially different directional changes. Similarly, waves originating from the same location but propagating under different initial angles may follow different paths through the magnetic field.

Under suitable conditions, multiple trajectories connecting an emitting region with a distant observer may become possible. Their existence depends on the strength and spatial distribution of the proposed magnetic interaction and cannot be assumed for every magnetic configuration.

The optical behavior of the sunspot is further complicated by the hypothesized coexistence of freely propagating waves, magnetically

guided waves, and waves released from magnetic channels.

The resulting optical system therefore cannot be adequately represented by a single focal point, a constant radius of curvature, or a conventional thin-lens approximation.

9.2. Dependence on the Observer's Viewing Direction

The observable structure of a sunspot depends on the propagation directions of electromagnetic waves reaching a distant observer.

For an observer located at a point T, each direction of observation corresponds to a particular element of the solar image.

The apparent brightness of that element is determined by the radiation arriving from the corresponding direction, rather than by the total radiation passing through the surrounding region of space.

In the proposed magnetic-deflection model, the final propagation direction of an electromagnetic wave does not necessarily indicate its original direction or its actual point of emission.

A ray traced backward along its final straight trajectory may therefore indicate an apparent source position different from the physical location at which the radiation emerged from the photosphere.

The optical mapping between the emitting surface and the observer may change as the sunspot moves across the visible solar disk.

Different viewing directions select different sets of electromagnetic-wave trajectories passing through the magnetic structure.

This dependence is particularly relevant to the penumbra, where spatial variations in magnetic-field geometry may influence the appearance, orientation, and contrast of individual filaments.

In contrast, radiation remaining confined within closed magnetic loops would not become directly visible merely because the observer changes the viewing direction. Such radiation could contribute to the observed image only after escaping from its guiding structure.

9.3. Apparent Changes in Sunspot Shape and Size

The apparent shape of a sunspot changes as its position on the visible solar disk changes.

A substantial part of this variation results from ordinary geometrical projection. An approximately circular region observed obliquely appears narrower in the direction toward the solar limb.

The independently observed depression of the umbral surface, known as the Wilson depression, also contributes to viewing-angle-dependent changes in sunspot appearance. [1] [2]

In addition to these established effects, the present model investigates the possibility that magnetic deflection may modify the apparent positions of radiation sources.

Electromagnetic waves emerging from different parts of the photosphere may follow curved trajectories before leaving the magnetic structure.

The observer identifies their apparent positions according to their final propagation directions.

The apparent boundaries of the umbra and penumbra may therefore differ from the physical boundaries of the corresponding photospheric regions.

Such optical displacement could, in principle, contribute to changes in the apparent width, shape, or internal structure of the sunspot when observed from different directions.

However, the magnitude of this proposed effect has not yet been established.

A quantitative investigation must distinguish magnetic optical displacement from ordinary geometrical projection, the Wilson depression, and actual changes in the physical structure of the sunspot.

9.4. Limits of a Simplified Ray Model

Preliminary investigations using simplified magnetic-field distributions demonstrate the considerable complexity of the proposed optical problem.

Even when the magnetic-field strength is represented by a smooth Gaussian distribution, the calculated electromagnetic-wave trajectories depend on the source position, the initial propagation direction, and the magnetic gradients encountered along the path.

Changes in the spatial distribution of the magnetic field may alter the curvature of neighboring trajectories and, under suitable model conditions, produce multiple propagation paths.

However, such geometrical calculations do not independently determine the observed brightness distribution.

The convergence of electromagnetic-wave trajectories in space must be distinguished from the directional radiance measured by an observer.

A redistribution of ray directions does not necessarily produce a reduction in the apparent surface brightness of an extended radiation source.

Furthermore, the proposed magnetic capture mechanism introduces an additional physical process that cannot be represented solely by gradual ray deflection.

Stable propagation along relatively small magnetic loops requires the electromagnetic wave to attain a radius of curvature compatible with the local curvature of the magnetic structure.

The conditions for entering and maintaining this guided regime remain to be established.

Simplified ray calculations are therefore useful for exploring individual geometrical properties, but they do not provide a complete solution to the optical formation of a sunspot.

9.5. Mathematical Optical Analysis as an Open Research Problem

The magnetic structure of a sunspot constitutes a potentially complex optical system whose complete mathematical description extends beyond the scope of the present article.

A quantitative treatment would require a three-dimensional representation of the magnetic field, including its large-scale geometry, local gradients, characteristic radii of curvature, and smaller spatial disturbances.

It would also require a description of the angular distribution of photospheric radiation and a physically established interaction law governing the curvature of electromagnetic-wave trajectories.

Particular attention should be given to the conditions under which a freely propagating electromagnetic wave may enter a magnetically guided regime, remain confined within it, or subsequently escape.

Based on these conditions, the trajectories of electromagnetic waves could be calculated from their photospheric origins through the magnetic structure to their final propagation directions.

The principal objective of such an investigation would be to determine the directional brightness distribution observed from a distant observation point T.

This calculation should establish whether the proposed magnetic interaction can reproduce the darkness of the umbra, the intermediate brightness and filamentary structure of the

penumbra, and the relatively distinct boundaries separating these regions.

The mathematical analysis must also respect electromagnetic energy conservation and distinguish spatial concentration of radiation from changes in observed radiance.

The present article does not attempt to provide a complete numerical solution to this problem. Its purpose is to identify the proposed physical mechanisms, establish their conceptual relationships, and formulate the conditions under which their optical consequences can be investigated.

The detailed mathematical development of this magnetic optical system is left to future research.

The observational consequences and possible experimental tests of the proposed model are considered in the following chapter.

The provisional return fractions reported in Section 3.6 must be reproduced from a documented three-dimensional integration, including the exact guiding force, angular response, damping prescription, source angular distribution, and trajectory termination criteria, before they can be treated as quantitative predictions. In particular, the relatively high model fractions obtained outside the nominal umbral boundary for oblique rays are a substantive test of the assumed interaction rather than evidence of an observed effect.

10. Observational Consequences and Experimental Tests

10.1. Predicted Dependence of Brightness on Magnetic Field Strength

The proposed optical interpretation of sunspots establishes a possible relationship between the magnetic environment and the fraction of photospheric radiation available for direct observation.

Within the umbra, strong magnetic fields and suitable magnetic-channel configurations are hypothesized to capture a substantial fraction of the emerging electromagnetic radiation.

Toward the penumbra, changes in the magnetic environment may reduce the effectiveness of capture, allowing a greater fraction of the radiation to escape.

The model therefore suggests a possible relationship between local brightness and the conditions required for magnetic guidance.

However, this relationship cannot be expressed solely in terms of magnetic-field strength. The proposed interaction also depends on transverse magnetic gradients, the initial propagation directions of electromagnetic waves, and the curvature of the magnetic structure.

Of particular importance is the relationship between the attainable radius of curvature of electromagnetic-wave trajectories and the local radius of curvature of magnetic channels.

Two photospheric regions with approximately equal magnetic-field strengths may therefore exhibit different capture efficiencies if their magnetic geometries differ.

A useful observational investigation would compare the brightness distribution of sunspots with independently determined magnetic-field strengths, gradients, inclinations, and magnetic-loop configurations.

Such comparisons should also include measurements of atmospheric temperature and plasma properties.

The objective would be to determine whether the observed brightness contains a systematic dependence on magnetic geometry that cannot be fully accounted for by conventional radiative-transfer and magnetoconvective models.

A correlation between magnetic-field strength and reduced brightness alone would not distinguish the proposed capture mechanism from established solar physics.

10.2. Relationship Between Magnetic Gradients and Penumbral Filaments

The proposed interpretation of the penumbra associates its filamentary appearance with spatial variations in magnetic capture and the deflection of escaping electromagnetic radiation.

Local magnetic disturbances may modify the curvature of electromagnetic-wave trajectories and consequently change the distribution of radiation reaching the observer.

If this mechanism contributes significantly to the appearance of the penumbra, some systematic relationship should exist between the observed optical structures and the spatial organization of magnetic gradients.

However, a direct geometrical correspondence between individual magnetic disturbances and individual visible filaments is not necessarily expected.

The proposed optical response depends on the accumulated interaction along the entire propagation path. A single magnetic disturbance may influence numerous trajectories, while several disturbances may contribute to a single optical feature.

An appropriate observational investigation should therefore combine high-resolution continuum imaging with simultaneous spectropolarimetric measurements of the magnetic field.

Particular attention should be given to the orientation, length, contrast, and temporal evolution of individual penumbral filaments.

Measurements of plasma velocities and temperature variations would provide additional information necessary to distinguish apparent optical changes from the actual motion and thermal evolution of photospheric matter.

The objective is not merely to establish a correlation between magnetic structures and visible filaments, but to determine whether their relationship is consistent with the proposed directional redistribution of electromagnetic radiation.

A discriminating comparison should use co-registered spectropolarimetric magnetic-field maps and continuum images, taking care not to identify a local ray-convergence pattern directly with radiance enhancement. Both the angular distribution of incident radiation and capture or release along the entire trajectory must be included.

10.3. Radiation Associated with Magnetic Loop Instabilities

The hypothesis of guided electromagnetic propagation along magnetic loops introduces an additional possibility for observational investigation.

If electromagnetic radiation can remain confined within a magnetic channel, disturbances of the channel may modify the conditions required for stable guidance.

A sufficiently large change in magnetic-field geometry, transverse gradients, or local curvature may cause previously guided radiation to escape.

The direction of the released radiation would be related to the propagation direction of the electromagnetic wave at the point of release.

Changes in the geometry of a magnetic loop could therefore produce changes in the direction and intensity of the radiation escaping from it.

The most demanding conditions are expected in strongly curved magnetic structures, where the required radius of curvature of the

electromagnetic-wave trajectory is relatively small.

Observational investigations could examine whether transient radiation associated with magnetic-loop disturbances exhibits directional, spectral, or polarization properties consistent with the release of previously guided radiation.

In particular, attention could be given to the relationship between the radiation spectrum and the spectrum of the photospheric region associated with the magnetic loop.

The proposed mechanism must be distinguished from conventional emission produced by plasma heating, excitation, ionization, and magnetic reconnection.

The observation of a bright magnetic loop or a transient brightening is therefore not sufficient to demonstrate electromagnetic-wave guidance.

A further consequence of the model concerns the receiving regions of magnetic loops.

If a substantial fraction of photospheric radiation is transported from a source toward a spatially separated sink, the receiving region must participate in the corresponding energy balance.

The identification of such an energy transfer would provide an important additional test of the magnetic-capture hypothesis.

10.4. Dependence on Viewing Angle

The passage of a sunspot across the visible solar disk provides an opportunity to investigate its appearance from different viewing directions.

As discussed in Chapter 9, the optical mapping produced by a magnetic structure may depend on the orientation of the electromagnetic-wave trajectories relative to the observer.

Changes in viewing direction may therefore modify the apparent distribution of radiation escaping from the penumbral magnetic region.

Under the proposed model, the contrast, apparent position, and shape of individual penumbral filaments may exhibit a systematic dependence on viewing direction.

The umbra provides a different test.

Radiation that remains confined within closed magnetic loops would not become directly visible merely because the observer changes position relative to the magnetic-field direction.

Consequently, the proposed capture mechanism could contribute to reduced umbral brightness over a broad range of viewing angles.

A useful investigation would follow the same sunspot during its passage across the solar disk and compare its brightness distribution, apparent dimensions, and filamentary structure at different heliocentric angles.

Ordinary geometrical projection, photospheric limb darkening, the Wilson depression, and temporal changes in the physical structure of the sunspot must be included in the analysis.

After accounting for these established effects, any remaining systematic variation could be examined in relation to the proposed magnetic optical mechanism.

Quantitative predictions would require the three-dimensional optical analysis outlined in Chapter 9.

10.5. Laboratory Tests of Magnetic Deflection and Capture

The proposed magnetic interaction with electromagnetic waves should ultimately be investigated under controlled laboratory conditions.

Solar observations alone cannot independently establish the existence of a magnetic force acting on freely propagating electromagnetic radiation, since the solar atmosphere contains numerous interacting physical processes.

The first experimental objective should therefore be to determine whether a nonuniform external magnetic field can produce a measurable change in the propagation direction of electromagnetic radiation under conditions where conventional optical and plasma effects are sufficiently controlled.

A narrow electromagnetic beam could be directed through a region of known magnetic-field distribution.

The transverse magnetic gradient, propagation direction, and interaction length could be varied independently.

Measurements of the emerging beam position and direction would provide information about the possible curvature of its propagation path.

The known spatial distribution of the magnetic field would then allow the effective radius of curvature to be estimated and compared with the predictions of Part D3.

Experiments should also examine whether the proposed deflection depends on electromagnetic wavelength, polarization, beam intensity, or the orientation of the propagation direction relative to the external magnetic field.

Measurements performed in vacuum would be particularly valuable for distinguishing the proposed direct magnetic interaction from conventional magneto-optical effects in matter.

A second experimental objective would be to investigate whether electromagnetic radiation can enter a stable magnetically guided propagation regime.

For this purpose, a magnetic configuration with a known curved geometry could be established.

The experiment should determine whether electromagnetic radiation can remain associated with the magnetic structure while its propagation direction changes continuously along the curved path.

The required radius of curvature of the electromagnetic-wave trajectory would be determined by the geometry of the experimental magnetic channel.

Experiments with different channel curvatures and magnetic gradients could subsequently establish whether a critical condition separates guided propagation from freely escaping radiation.

The geometry and physical conditions of laboratory experiments need not reproduce the dimensions of solar magnetic loops. Their purpose is to investigate the existence and scaling of the proposed interaction under independently controlled conditions.

A successful demonstration of magnetic deflection would not, by itself, establish magnetic capture. Stable guided propagation must be demonstrated separately.

Conversely, experimental upper limits on the attainable curvature would provide important constraints on the applicability of the proposed mechanism to solar magnetic structures.

The experimental results could therefore establish whether the magnetic interaction developed in Part D3 is sufficiently strong to support the optical mechanisms proposed in Part D4.

The combination of laboratory experiments and astronomical observations offers a means of evaluating the proposed model independently of the qualitative similarities between its predicted optical structures and the observed appearance of sunspots.

11. Discussion

11.1. Comparison with Conventional Sunspot Models

Conventional interpretations of sunspots primarily associate their reduced brightness with the influence of magnetic fields on

convective energy transport. The resulting differences in temperature, plasma dynamics, and atmospheric structure provide the physical basis for established models of the umbra and penumbra.

The present study approaches the phenomenon from an additional perspective. Instead of considering exclusively the production and thermal transport of radiation, it investigates the possibility that the magnetic environment may also influence the propagation and directional redistribution of radiation after its formation.

The principal distinction lies in the role assigned to the magnetic field.

In conventional models, the magnetic field modifies the physical conditions of the emitting plasma and thereby influences the radiation produced by that plasma.

In the proposed model, the magnetic field may additionally act directly on the propagation of structured electromagnetic waves.

The resulting optical effects may include changes in propagation direction, magnetic capture, guided energy transport, and the spatial redistribution of escaping radiation.

The proposed interpretation does not require temperature reduction or the Wilson depression as initial causal assumptions for the optical mechanism.

An important objective of future research is therefore to determine whether magnetic redistribution of radiation constitutes a measurable contribution to the observed umbral and penumbral brightness.

11.2. Established Physics and Additional Hypotheses

The proposed interpretation combines established properties of the solar atmosphere with additional hypotheses derived from the structured electromagnetic-wave model developed in Parts B1–B4 and D3.

The established physical background includes the existence of strong magnetic fields in sunspots, the formation of photospheric radiation through interactions with matter, the presence of magnetic loops, and the spatial and temporal complexity of penumbral magnetic structures.

Part D3 introduces the hypothesis that a spatially structured E–B–P electromagnetic wave may experience a transverse interaction in a nonuniform external magnetic field.

The present article extends this hypothesis by considering the possibility of magnetic capture and sustained propagation along curved magnetic structures.

The radius of curvature of the electromagnetic-wave trajectory becomes a central parameter in evaluating this possibility.

For stable guidance, the electromagnetic wave must be capable of attaining the curvature required by the magnetic channel while remaining confined within it.

Relatively small magnetic loops associated with sunspots provide a particularly demanding test of this requirement.

The additional hypotheses introduced in Part D4 concern the directional distribution of radiation emerging from a magnetized photosphere, the efficiency of magnetic capture, the stability of guided electromagnetic propagation, and the release of radiation from magnetic structures.

These hypotheses are interconnected but must be investigated separately.

In particular, experimental confirmation of magnetic deflection would provide essential support for Part D3, while the existence of stable magnetic guidance and its efficiency would remain additional subjects of investigation.

11.3. Energy Balance and Physical Consistency

A fundamental requirement of the proposed interpretation is the conservation of electromagnetic energy.

If a substantial fraction of radiation emerging from the umbra enters magnetically guided propagation paths, its energy must remain accounted for throughout the transport process.

The reduced amount of directly escaping radiation must therefore be accompanied by energy transport toward other regions, subsequent radiation release, absorption by matter, or other physically identifiable energy-transfer processes.

The proposed magnetic-loop mechanism establishes a conceptual connection between a photospheric source and a spatially separated receiving region.

Such transport could modify the spatial distribution of radiative energy in the solar atmosphere.

However, the hypothetical capture of approximately 90% of locally available outward radiation would represent a significant redistribution of energy. Its broader consequences for the thermal and radiative balance of the solar atmosphere must therefore be investigated.

The corresponding power cannot be inferred solely from the apparent darkness of the umbra, since the observed directional intensity and the total radiative power are different physical quantities.

A complete energy balance would provide an independent means of evaluating the proposed mechanism.

The momentum balance must also be considered. Sustained curvature of an electromagnetic-wave trajectory requires a continuous change in the direction of its momentum. The corresponding momentum exchange with the magnetic structure and its physical sources must be included in a complete description.

These requirements establish important conditions that any future quantitative development of the model must satisfy.

11.4. Unresolved Mechanisms and Future Research

The present investigation identifies several physical and mathematical problems that remain open.

The first concerns the microscopic origin and strength of the proposed interaction between a structured electromagnetic wave and an external magnetic field.

The second concerns the transition between freely propagating radiation and magnetically guided radiation, including the conditions required for stable propagation along strongly curved magnetic channels.

The third concerns the angular distribution of radiation emerging from the magnetized photosphere and the fraction of radiation capable of entering the guided propagation regime.

The fourth concerns the complete optical mapping produced by the three-dimensional magnetic structure of a sunspot.

This optical system includes spatially varying trajectory curvatures, changes in the direction of bending, partial capture, guided propagation, and the subsequent release of electromagnetic radiation.

Its mathematical description is substantially more demanding than the analysis of a conventional optical lens.

A complete calculation must determine the intensity distribution received by an observer from individual directions while respecting radiative-transfer constraints, energy conservation, and momentum conservation.

The present article establishes the conceptual framework for such an investigation but leaves its detailed mathematical solution to future research.

Particular importance is assigned to laboratory measurements of magnetic deflection and the minimum attainable radius of curvature of electromagnetic-wave trajectories.

These measurements could establish whether the interaction proposed in Part D3 is sufficiently strong to support electromagnetic guidance along the relatively small magnetic loops considered in Part D4.

The investigation of sunspots also provides a conceptual basis for Part D5, in which the possible optical influence of large-scale stellar magnetic structures is examined in relation to the periodic brightness variations of Cepheid stars.

Taken together, these investigations explore whether the interaction between electromagnetic radiation and nonuniform magnetic fields may represent an additional mechanism contributing to the observed optical characteristics of astronomical objects.

12. Conclusions

The present article develops a conceptual model of sunspots based on the proposed interaction between structured electromagnetic waves and nonuniform magnetic fields.

Building on the magnetic-deflection mechanism introduced in Part D3, the investigation extends the analysis from freely propagating electromagnetic waves to radiation originating within strongly magnetized regions of the solar photosphere.

The central hypothesis is that the magnetic structure of a sunspot may capture a substantial fraction of the emerging photospheric radiation and guide it along curved magnetic channels.

The radius of curvature of the electromagnetic-wave trajectory is identified as a fundamental geometrical parameter of the proposed mechanism. Stable magnetic guidance requires the wave to attain a curvature compatible with that of the guiding magnetic structure.

Relatively small magnetic loops provide an important criterion for evaluating the physical feasibility of this process.

Within the proposed interpretation, the captured electromagnetic radiation may propagate from a photospheric source along a magnetic loop toward a spatially separated receiving region. The energy is thereby redistributed rather than removed from the physical system.

Efficient magnetic capture could contribute to the darkness of the umbra, while a reduction in capture efficiency toward the surrounding penumbra could allow a greater fraction of photospheric radiation to escape.

The escaping electromagnetic waves may remain subject to the optical influence of spatial variations in the magnetic field.

The penumbral magnetic structure may consequently act as a complex optical system in which variations in magnetic gradients and trajectory curvature influence the distribution of radiation reaching an observer.

This proposed mechanism provides a common conceptual framework for investigating the darkness of the umbra, the intermediate brightness of the penumbra, its filamentary structure, and the relatively distinct optical boundaries of sunspots.

The framework also identifies possible relationships between magnetic-loop geometry, radiation transport, energy release, and the apparent structure of the solar atmosphere.

The complete mathematical description of this optical system, including the conditions for

magnetic capture and its quantitative efficiency, remains an open research problem.

Laboratory experiments investigating magnetic deflection and guided electromagnetic propagation, together with astronomical measurements of sunspot brightness, magnetic geometry, and radiation spectra, offer possibilities for independent verification.

The broader significance of the proposed model extends beyond the interpretation of sunspots. If the hypothesized interaction between electromagnetic waves and external magnetic fields is confirmed, magnetic structures may need to be considered not only as factors influencing the generation of stellar radiation but also as active systems governing its propagation and directional distribution.

This possibility provides the foundation for the subsequent investigation of Cepheid stars in Part D5.

The illustrative minimum ray-curvature radius of 1000–2000 km, the representative value of 1500 km, and the fractions of returning radiation in Section 3.6 are working model inputs or preliminary estimates. They should not be interpreted as independently measured properties of solar light. A decisive next step is a reproducible coupling-and-trajectory calculation constrained by measured magnetic geometries and solar radiance.

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