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S.I.: NEW THINKING ABOUT SCIENTIFIC REALISM

Predictive success, partial truth and Duhemian realism

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Abstract According to a defense of scientific realism known as the "divide et impera move", mature scientific theories enjoying predictive success are partially true. This paper investigates a paradigmatic historical case: the prediction, based on Fresnel's wave theory of light, that a bright spot should figure in the shadow of a disc. Two different derivations of this prediction have been given by both Poisson and Fresnel. I argue that the details of these derivations highlight two problems of indispensability arguments, which state that only the indispensable constituents of this success are worthy of belief and retained through theory-change. The first problem is that, contrary to a common claim, Fresnel's integrals are not needed to predict the bright spot phenomenon. The second problem is that the hypotheses shared by to these two derivations include problematic idealizations. I claim that this example leads us to be skeptical about which aspects of our current theories are worthy of belief.

Keywords Scientific realism · Partial truth · Novel prediction · Fresnel's bright spot prediction · Divide et impera move · Pierre Duhem

1 Introduction

In its broader understanding, scientific realism is the claim that our scientific theories are true, i.e. that they describe mind-independent realities of nature. While this is an old philosophical thesis, which has known a handful of different versions, most

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of today's realists agree that the best argument to defend it has been first proposed by Duhem (1914, p. 37) and reformulated by Smart (1968), Hilary Putnam (1975), Alan Musgrave (1988) and Jarett Leplin (1997). This argument is the no-miracle argument based on predictive success: it claims that theories enjoying predictive success are true, because truth is the only explanation that does not make this success a miracle.

A common objection to scientific realism is the so-called "pessimistic induction" (Laudan 1981): since past theories have been rejected, present and future theories are likely to be rejected too. Moreover, among these past theories, some enjoyed predictive success but postulated entities and relations which are now believed to be false. Fresnel's wave theory of light is a strong case in favor of this objection because it led to successful novel predictions while supposing the existence of *optical ether*, an entity rejected by physicists at the end of the 19th century.

The realist's answer to the pessimistic objection is often to reduce her claim from truth to partial truth. One of the clearest formulation of this answer is the *divide and impera move* proposed by Stathis Psillos, which provides an achievable procedure to identify the true parts of a theory:

> How should realists circumscribe the truth-like constituents of past genuinely successful theories? I must first emphasise that we should really focus on the specific successes of certain theories, like the prediction by Fresnel's theory of diffraction that if an opaque disk intercepts the rays emitted by a light source, a bright spot will appear at the centre of its shadow [...]. Then we should ask the question: how were these successes brought about? In particular, which theoretical constituents made essential contribution to them? [...]
>
> Theoretical constituents which make essential contributions to successes are those that have an indispensable role in their generation. They are those which really "fuel the derivation". (Psillos 1999, p. 110)

The next issue is to characterize what it is to have an "indispensable role" in the generation of a prediction (i.e. predictive indispensability). Here again, Psillos does not avoid the problem:

> When does a theoretical constituent H indispensably contribute to the generation of, say, a successful prediction? Suppose that H together with another set of hypotheses H' (and some auxiliaries A) entails a prediction P. H indispensably contributes to the generation of P if H' and A alone cannot yield P and no other available hypothesis H^* which is consistent with H' and A can replace H without loss in the relevant derivation of P. (Psillos 1999, p. 110)

This paper investigates the scope of Psillos' divide et impera strategy. At first sight, it seems that it can be understood as a special kind of indispensability argument, relying on *predictive indispensability*:

1. The constituent H of a scientific theory T is indispensable to its predictive success.
2. If a constituent of a scientific theory is indispensable to its predictive success, then it is worthy of belief and will be retained in theory-change.
3. Therefore: H should be worthy of belief and will be retained in theory-change.

In this paper, I show that the divide et impera move should not be used as an indispensability argument, because this argument is unsound. In Sect. 2, I investigate the historical details of the prediction of the bright spot. In Sects. 3 and 4, I argue that premise 1 can be asserted only from the vantage point of a theory superseding T. In Sect. 5, I show that if premise 2 were true, then history of science would be a predictable process. Finally, I argue that a careful realist stance inspired by Duhem's conception of the no-miracle argument does not need any indispensability argument and avoids these problems.

2 Two derivations of the bright spot prediction

The bright spot prediction is one of the most discussed examples of novel prediction. The story of this folkloric episode has been told in detail and de-romanticized by John Worrall (1989a). In 1818, Fresnel's *Mémoire sur la diffraction* was presented at the Académie des sciences in Paris. According to the *Rapport sur le Mémoire de M. Fresnel* written by Arago, one of the members of the jury, Poisson, proved the two following consequences of Fresnel's wave theory of light: the presence of a dark spot at the center of the projection of light diffracted by a circular opening, and the presence of a bright spot at the center of the shadow of a circular screen (Fresnel 1866, p. 245).[1] Arago successfully performed the experiment and confirmed these novel predictions. As Worrall argues, this discovery may not have had an important confirmatory weight, but it is often considered as a novel prediction supporting the no-miracle argument [notably by Worrall himself (Worrall 1989b, p. 114)].

The reception of this successful prediction and the reformulation of Fresnel's wave theory by Maxwell have been extensively studied. Yet, the details of the *derivation* of this prediction—necessary to circumscribe the indispensable constituents of Fresnel's theory success—have not been sufficiently scrutinized. In this section, I study the two derivations made at that time by Poisson and Fresnel.

2.1 Poisson's proof

Unfortunately, we do not have historical records of Poisson's proofs of the bright spot and of the dark spot. However, Arago's *Rapport* mentions clearly the use of Fresnel's integral by Poisson to predict the dark spot. Moreover, in a *Note* following his *Mémoire*, Fresnel claims that Poisson gave him the proof of the *bright* spot prediction (Fresnel 1866, p. 365). We can then assume that Poisson used Fresnel's integral in both cases.[2]

Consequently, the first constituent of Poisson's proof is Fresnel's integral for the intensity of light. This integral embeds Huygens' principle:

> The vibrations of a light wave in each of its points may be seen as the sum of the elementary motions that would be sent there, at the same instant, by all the

[1] Note that the bright spot phenomenon was not the only one predicted by Poisson. The dark spot is more complex than the bright spot, because the diffraction of white light through a circular aperture produces diffraction rings of different colors surrounding the dark spot.

[2] I give in the appendix a modern derivation of the bright spot prediction based on Fresnel's integral.

parts of this wave considered at any arbitrary anterior position. (Fresnel 1866, p. 293)

To apply this principle and Fresnel's integral to the computation of the intensity of light at the center of the shadow of a disc, Poisson must have used a relation in order to link the intensity of light to some property of the light wave. This property is its amplitude: intensity equals the square of the wave amplitude.

Fresnel's integral is extremely difficult to solve if the diffraction is made by an object or an aperture with a complex shape. Yet, Arago mentions that Poisson noticed that "the integral that represents the intensity of diffracted light could be *easily* obtained for the center of the shadow of a circular screen or opening" (Fresnel 1866, p. 245) [my italics]. We can then assume that Poisson hypothesized that the disc casting a shadow was *perfectly* circular.[3]

In addition, Poisson must have used another hypothesis. In the case of light diffraction by a disc, the diffracted light wave occupies all the space from the edge of the disc to infinity (see Fig. 1 in the appendix). To solve Fresnel's integral, Poisson must have accepted the following boundary condition: at infinity, the integral's value is null, as if light rays infinitely far away from the screen were geometrical rays, which are not diffracted.

Even if we do not have any document indicating clearly the way Poisson's proof unfolded, we can still apply Psillos' divide et impera move. The constituents of Poisson's derivation of the novel prediction are the following propositions :

P1 *A law*: Fresnel's integral (embedding Huygen's principle).
P2 *A relation* between intensity and the wave amplitude: intensity is proportional to the square of amplitude ($I = u^2$).
P3 *A simplifying assumption*: the screen casting a shadow is a perfectly circular object.
P4 *A boundary condition*: at infinity the integral's value is null.

If any of the constituents of the preceding list is removed, it is not possible to derive the bright spot prediction. If Poisson's proof was the only one, it could seem that these constituents are indispensable to the predictive success of Fresnel's theory. But Fresnel gave his own derivation of the same prediction, which is based on a different set of hypotheses.

2.2 Fresnel's proof

The only proof of the prediction of the bright spot and of the dark spot given by Fresnel himself is in the *Note 1* following his memoir (Fresnel 1866, pp. 365–372). In this proof, Fresnel intends "to give the simplest solution to these two problems, *without*

[3] The case of an irregular circular screen was solved in the 1980s with the help of computer simulations (see (Harvey and Forgham 1984)). Even if Poisson was an outstanding mathematician, he would not have "easily" solved the case of an irregular circular screen. Moreover, these simulations show that the bright spot phenomenon is very sensitive to small-scale deviations from the ideal circular case. A regular sinusoidal corrugation of the circular shape of amplitude 100 μm edge almost completely removes the central bright spot. It is therefore necessary to assume that the screen is *perfectly* circular, and not only *roughly* circular.

the help of the integrals used in the preceding memoir to compute other diffraction phenomena." (Fresnel 1866, p. 365) [my italics]

Fresnel begins with the case of the dark spot at the center of the projection of a circular *opening*. First, he builds a geometrical model of the incident wave when it is diffracted by a circular opening. He assumes that the surface of the opening is divided into a sequence of concentric rings that have the same areas. Therefore, the same amount of rays passes through each ring, which have the same contribution to the intensity of light (Fresnel 1866, p. 365).

Fresnel then assumes that the rays sent by two consecutive rings have a difference of phase of "half an oscillation", i.e. half a wavelength.

> Consequently, all the rays sent at the center of the projection of the opening by two consecutive rings completely destroy each other. If the number of rings is even, then there will be a complete destruction of all the elementary waves emanated by the incident wave, and the center of the projection of the opening will be deprived of light. (Fresnel 1866, p. 366)

This is a simple proof of the possible existence of a dark spot at the center of the projection of a circular opening, without any use of Fresnel's integrals.

Fresnel then hypothesizes "that the circular opening is infinitely large" (Fresnel 1866, p. 367). In that case "the vibrations coming from each ring are destroyed by the half of the absolute speed brought by the previous ring, and by half of the absolute speed brought by the following ring" (Fresnel 1866, p. 366). "Absolute speed" here refers to the particles of ether. In this framework, the particles of ether oscillate before returning to a state of absolute rest. Thus, in Fresnel's model, half of the vibration of ethereal particles coming from one ring is destroyed by interference with the rays of the previous ring, and the other half is destroyed by interference with the following ring. Therefore, the small ring at the center of the infinitely large opening will have only half of its "absolute speed" destroyed. The contribution of any other ring is destroyed by the rays coming from the surrounding rings. Fresnel then makes the assumption that the extreme ring being at infinity, its contribution counts as nothing. As a consequence, if the opening is infinitely large, only half of the absolute speed of the smallest ring contributes to the intensity of light. The intensity of light is defined as proportional to the square of the absolute speed of these particles. Therefore, the intensity at the center of the projection is the quarter of the intensity of light source.

In the following paragraph, Fresnel describes the case of the diffraction by a circular screen, i.e. the bright spot. Fresnel also starts by building a geometrical model: he divides the light wave around the screen in a sequence of rings of the same areas. Once again, each ring's contribution is destroyed by the rays coming from the surrounding rings, "so that only half of the vibrations of the rays of the ring contiguous to the screen remains" (Fresnel 1866, p. 368).

To conclude its proof, Fresnel only have to show that the case of the circular screen and the case of the infinitely large opening are identical:

> Now, this ring [contiguous to the screen] has the same area than a small ring inside an infinitely large opening. In that case, the center of the shadow of a circular screen must be illuminated as if there was no screen.

This analogy proves that there should be a bright spot at the center of the shadow, and that it should have one fourth of the source intensity. It is the same conclusion than Poisson's proof.

The constituents of Fresnel's prediction are the following propositions:

F1 *A definition*: light rays are waves of ether that can interfere and be diffracted.
F2 *A relation* between intensity and the absolute speed of ethereal particle: the square of the absolute speed of ethereal particles is proportional to the intensity of light ($I \propto |v|^2$).
F3 *A simplification*: the screen casting a shadow is a perfectly circular object.
F4 *An identity*: a circular opening with an infinitely large radius is identical to the absence of obstacle.
F5 *A geometrical model*: the space inside a circular opening or around a circular screen is divided into rings of the same areas, and the wavelength of the rays passing through these rings differ of half an oscillation.

The fact that two derivations of the same prediction exist—and that both are based on Fresnel's wave theory of light and several idealizations but not on Fresnel's integral—raises the following questions :

1. Which derivation is the proper one for the divide et impera move, the one that gives us the "true" constituents of Fresnel's wave theory of light? Do the two derivations have something in common?
2. Are idealizations indispensable to novel predictions? Do they undermine the soundness of the divide et impera move?

These questions are discussed in the next two sections.

3 Deflating predictive indispensability

3.1 Differences and similarities between Poisson's proof and Fresnel's proof

The bright spot case shows that the divide et impera move is difficult to apply to real historical cases, because when different derivations of the same prediction are available, it is not an easy task to see what they have in common and to what extent they differ.

Resemblance is a matter of degree, and it may appear to some readers that Fresnel's proof is very similar to Poisson's proof. Both are based on Fresnel's theory of light and endeavor to consider the way light rays are diffracted and interfere. But there are some important differences. In Poisson's proof, Fresnel's integral (P1) is used as a law to compute the intensity of light at the center of the shadow. This integral is the mathematical translation of Huygen's principle: it sums up the contribution of *all* parts of the light wave on *all* its previous positions. In Fresnel's proof the geometrical model F5 is sufficient to prove that the contributions of contiguous rings cancel one another—except for the smallest ring on the edge of the screen. This model removes the need to compute the contribution of *all* the diffracted wave front as requested by Huygen's principle. It is sufficient to assume that light rays interfere (this is the role of definition F1) in order to prove that only half of the vibrations of the smallest ring contributes to the intensity of light at the center of the shadow.

Consequently, Fresnel should be taken seriously when he speaks of a proof "without the help of [his] integrals". Poisson's proof and Fresnel's proof are not identical but illustrate two different ways to derive predictions. In Poisson's proof, it is the covering law P1 that fuels the prediction. In Fresnel's proof, this covering law is not needed, thanks to the way the physical system is represented by the geometrical model F5. This is this model and the mechanism of destructive interference (embedded in definition F1) that fuel the prediction.

Some readers could also consider that because the bright spot phenomenon was known at the time of Fresnel's derivation, it should not count as a prediction but as an explanation or a retrodiction.

There is no doubt that Fresnel's derivation was published after Arago performed the experiment of the bright spot for the first time and is not *temporally novel*. But *temporal* novelty is not the only way to characterize the novelty of a predicted phenomenon, and it is difficult to see how a temporal characterization of novelty should be of any importance for the issue of realism.

Musgrave (1974) has described two other types of novelty: theoretical novelty and heuristic novelty (also known as use-novelty). A phenomenon is *theoretically* novel for a theory if it is not predicted by any of that theory's extant rivals. As such, Fresnel's derivation is indeed theoretically novel: no other theory than the wave theory of light could predict the bright spot phenomenon.[4]

There are some debates concerning the definition of heuristic novelty [see (Alai 2014, section 3) for a review], but the underlying intuition is that a phenomenon is *heuristically* novel—or *use*-novel—for a theory if the theory was not constructed specifically to accommodate this phenomenon. Fresnel's geometrical model is not used primarily to predict the bright spot phenomenon, but to predict the dark spot phenomenon (see Sect. 2.2) as well as the intensity and color of the colored ring surrounding this dark spot (Fresnel 1866, p. 372). It is therefore difficult to argue that Fresnel's derivation is *less* use-novel than Poisson's proof.[5]

If both derivations count as novel predictions, then Fresnel's integral (P1) can be replaced by a definition and a geometrical model (F1 and F5). Thus, according to the divide et impera move, these integrals are not indispensable for the predictive success of Fresnel's theory of light. Yet, these equations have been retained through theory-change: Fresnel's integrals are deducible from Kirchhoff's equations and Green's

[4] It is true that supporters of a corpuscular theory of light (such as Laplace, Biot or Poisson) did reformulate their own theory to take diffraction phenomena into account. But, to my knowledge, they offered no derivation of the bright spot phenomenon in the framework of their reviewed corpuscular theory.

[5] This distinction between three kinds of novelty has been discussed in the context of the theory of confirmation. In the context of realism, Mario Alai argues that a predicted fact is novel enough to fuel the no-miracle argument if it is *a priori improbable* and *heterogeneous* with the old empirical data, i.e. "not inferable from these data by a standard generalization procedure" (Alai 2014, p. 310). On that account, Fresnel's prediction should also be considered as novel: the bright spot is a priori improbable without a wave theory of light, and it cannot be extrapolated from other diffraction data such as the ones presented by Fresnel in his memoir.

theorem, and it is through this deduction that our present theory of light accounts for Fresnel's theory success.

Psillos' divide et impera move, in its original formulation, does not imply that idle (i.e. dispensable) constituents of a theory's predictive success should disappear in future theories. Yet, other authors suggest that it should be the case. Peter Vickers, for example, in his study of the boundary conditions in one of Kirchhoff's predictions, claims that it is possible to make "the interesting and substantial prediction concerning the future of science: that those idle aspects of the boundary conditions would not survive future scientific change" (Vickers 2013, p. 209). But some hypotheses, such as Fresnel's integral, can be dispensable and yet retained in theory-change.

3.2 The common core of indispensable constituents

We could, however, consider that the similarities between Fresnel's and Poisson's proofs are sufficient to circumscribe a common core of indispensable constituents.

There is clearly a common claim behind Fresnel's integral (P1) and the definition of light as a wave of ether (F1): the behavior of light exhibits oscillatory and periodic aspects which account for destructive and constructive interference, because wavefronts adjacent in space are alternatively in opposite phases, and opposite phases cancel out and equal phases reinforce. In the same vein, the relation between intensity and wave amplitude (P2) on the one hand, and between intensity and the absolute speed of ethereal particles (F2) on the other hand, do make a common claim: intensity of light is proportional to the square of one of an intrinsic characteristic of light. The simplifications P3 and F3 are identical: the screen casting a shadow is a perfectly circular object. Finally, the boundary conditions of both derivations (P4 and F4) hypothesize that light rays infinitely far away from an object behave as geometrical rays and are not diffracted.

As a result, the list of constituents common to both Poisson's and Fresnel's derivations of the bright spot prediction is the following:

- C1 *A postulate*: the behavior of light exhibits oscillatory and periodic aspects which account for destructive and constructive interferences: adjacent parts of a light beam are alternatively in opposite phases and opposite phases cancel out and equal phases reinforce.
- C2 *A relation*: intensity of light is proportional to the square of one of the intrinsic characteristics of light.
- C3 *A simplification*: the screen casting a shadow is a perfectly circular object.
- C4 *A boundary condition*: light infinitely far away from an object is not diffracted.

This list shows why the divide et impera move is an interesting strategy for the realist: it proves that ether does not fuel the success of Fresnel's theory.

Moreover, if the conjunction of C1, C2, C3 and C4 was sufficient to derive the bright spot prediction, then we would have circumscribed the working posits essential to the bright spot prediction. In the next subsection, I emphasize that this list of common constituents does not imply a strong ontological commitment toward crucial features of the nature of light. But first, it should be noted that these common constituents C1, C2, C3 and C4 are not sufficient to predict the bright spot phenomenon.

C1 is sufficient to predict that a circular screen produces interference phenomena. Yet, C1 alone is not sufficient to show that the superposition of the diffracted lightwaves at the center of the shadow is equal to the half of the amplitude of the incident wave. In other words, without Fresnel's integral (P1) or Fresnel's model (F5), it is impossible can link definition C1 with relation C2 and compute the intensity of light at the center of the shadow.

Without P1 or F5 but only the hypothesis that adjacent wavefronts are in opposite phase, we should expect that each wave amplitude is canceled by the adjacent one. We could not expect that half of the amplitude of the incident wave escape destructive interferences at the center of the shadow. Thus, P1 or F5 are necessary to derive the bright spot prediction, the common constituents listed above (C1-C4) are not sufficient to derive the bright spot.

P1 and F5 both rely on the assumption that adjacent wavefronts are alternatively in opposite phase, but they also play an inferential role in their respective proofs: each provides a different method to add up the different parts of the diffracted light to predict its amplitude at the center of the shadow.

It is important to note that Poisson's and Fresnel's proofs use a different kind of summation: P1 is an integral, whereas F5 is a geometrical model in which each ring's contribution is a discrete quantity added to the contribution of the adjacent rings.[6] In his proof, Fresnel assumes that all the rays going through one of the small ring surrounding the screen have the same wavelength. On the contrary, Poisson's use of Fresnel's integral implies that the propagation of light is a continuous phenomenon: there is no hiatus between two parts of the wavefront in opposite phase (see the "Appendix" for the application of Fresnel's integral to the case of the circular screen).

Obviously, from a mathematical point of view, P1 and F5 are very similar, because an integral is the continuous version of a summation. But from a physical point of view, P1 and F5 describe light differently. For P1, the wavefront and the propagation of light are continuous phenomena, but for F5 the light beam can be decomposed in discrete lightrays. Thus, these two assumptions may be considered as analogous from a mathematical point of view, but are incompatible if considered as assertions about the nature of light.[7]

Therefore, in addition of C1, C2, C3 and C4, the derivation of the bright spot requires a method to sum up the contribution of the diffracted light at the center of the shadow. Poisson's and Fresnel's proofs use different methods which lead to assumptions incompatible with each other. Thus, F1 and F5 are not "indispensable" if we accept Psillos' definition of indispensability, because they are incompatible

[6] In Fresnel's proof, the geometrical model F5 implies that we add up the "absolute velocity of ethereal particles" of the rays coming from one ring with the oscillation in opposite phase of two contiguous rings: the only ring having just one adjacent ring is the smallest, that is why half of its oscillation is not canceled and is found at the center of the shadow.

[7] Modern Quantum Physics has taught us that the same entity could be considered as a discrete particle or a continuous wave. However, these two accounts are still incompatible and mutually exclusive. As shown in the next subsection, Fresnel's wave theory of light was considered by its contemporary as compatible with an amended version of the corpuscular theory of light. But this claim would have been inconsistent if the hypothesis that light *really* propagates as a continuous wave had not been replaced by the assumption that light is composed of rays.

hypotheses and each one can be replaced by the other without loss in the derivation of the bright spot prediction.

3.3 A deflationist solution

Even if the list of constituents common to both proofs (C1-C4) is not sufficient to derive the bright spot, we could argue nonetheless that the divide et impera move warrants that it describe the true parts of Fresnel's theory of light. However, the common core of both derivations seems to deflate the ontological commitment resulting from Fresnel's theory success.

First of all, it should be noted that C1 was not introduced by Fresnel's wave theory of light. Corpuscular theories of light also attributed periodic and oscillatory behaviors to light in order to account for different phenomena such as polarization and diffraction. Biot, for example, when he formalized polarization at the beginning of the 19th century, attributed movement of rotation and oscillation to light "molecules" and thus assumed that light rays had oscillatory and periodic properties.[8] The real ontological innovation implied by Fresnel's theory is not that light has periodic and oscillatory behaviors, but that a light beam has a continuous wavefront and propagates continuously. Yet, this assumption is not indispensable to predict the bright spot, because, as we have seen, it is embedded in Fresnel's integral (P1) which can be replaced by a geometrical model (F5) based on the assumption—similar to the one of corpuscular theories—that a light beam is a cluster of separate lightrays.

That is why, as Worrall pointed out (Worrall 1989a, p. 140), it was possible for Poisson, Biot and Laplace to reformulate Huygen's principle and Fresnel's integrals in terms of light's "rays", a neutral term between corpuscular and wave theories of light. That is also why they did not adopt the wave theory even after Fresnel's predictive successes. They thought that the oscillations of "light's molecules" were equivalent to the oscillations Fresnel's theory attributed to light waves. Even if they were wrong, it shows that at the time the bright spot was predicted, it was not immediately clear, even to the best scientists in the field, which components of Fresnel's theory were essential. As I show in Sect. 5, this "opacity" of predictive success for the contemporaries of a theory is of critical importance to define partial truth.

If C1 has already been introduced by other theories than Fresnel's, the divide et impera move seems to make C2 the only original ontological commitment to the nature of light introduced by Fresnel. This view is compatible with Juha Saatsi's conception of Fresnel's theory of polarization (Saatsi 2005). For Saatsi, a minimal realist explanation of Fresnel's predictions only includes multiply realizable properties of light, which can be realized by different entities such as ether or electromagnetic fields. C2 is a similar assumption: it claims that some property of light (which can be the amplitude of light waves, absolute speed of ethereal particles or some other characteristic of light) is proportional to the square root of intensity.

[8] "We can give to the axis of polarization of light's molecules a conic oscillatory movement around the axis of translation. [...] This conception seems necessitated by a class of phenomena in which the light's molecules experience an ordinary refraction by a crystal, not only in a specific position of the principal section, but also left and right from this position" (Biot 1816, p. 284).

Finally, if C3 and C4 are two indispensable constituents of the bright spot's success, these propositions seem to describe objects and systems that do not exist in the physical world, and could therefore be considered as fictitious idealizations. This issue is discussed in the next section.

4 Indispensable idealizations

As Ronald Laymon suggested, idealizations can be considered "as intended antecedents for some species of counterfactual" (Laymon 1982, p. 108). On that account, C3 and C4 can be viewed as the antecedent of the following counterfactual statement: "if the screen casting the shadow was perfectly circular and if light at infinity was not diffracted, then it would cast a shadow with a bright spot in its center."

This section discusses the role and status of these constituents common to both Fresnel's and Poisson's proofs, and shows that it is difficult for the contemporaries of a theory to understand in which sense these idealizations are worthy of belief.

4.1 Idealization and de-idealization

Both Fresnel's and Poisson's proofs assume a perfectly circular screen (C3), an object that does not exist in nature or in human laboratories. A vast number of books and papers have been dedicated to the issue of idealization and realism (see, among others, Laymon 1982; McMullin 1985; Cartwright 2005; Uskali Mäki 2011; Bokulich 2012). Some authors have argued that such idealizations do not place scientific realism under suspicion but are in fact arguments for scientific realism. Ernan MacMullin, for instance, calls this kind of idealizations "Galilean idealizations" and affirms that they can be "de-idealized", i.e. that they are mere practical simplifications that can be eliminated with a more complete mathematical or experimental treatment of the physical system.[9] If one grants that C3 is a Galilean idealization, then it is not truly "indispensable". If it can be de-idealized, it can be eliminated.

However, we cannot apply the same de-idealization process to the boundary condition C4: "light infinitely far away from an object is not diffracted". David Batterman argues such idealizations are "cases of 'nontraditional' idealization in which idealizations actually play an essential, ineliminable role in explanatory contexts" (Batterman 2010, p. 19). One of Batterman's example is the explanation of the apparition of rainbows when light is diffracted by droplets:

> In the context of the rainbow patterns, we are in the realm of the wave theory or wave optics where lightwaves are governed by a wave equation. When we investigate the nature of this equation in the limit in which the wavelength of light approaches zero, we might expect to smoothly obtain ray or geometrical optics. [...] However, such a smooth limit does not exist. There are various math-

[9] Laymon's treatment of idealizations in physics is similar: "In compressed slogan form, the view proposed is this: a theory is confirmed if it can be shown that it is possible to show that more accurate but still idealized or approximate descriptions will lead to improved experimental fit; a theory is disconfirmed when it can be shown that such improvement is impossible" (Laymon 1982, p. 114).

> ematical blow-ups and singularities in the zero wavelength limit. Nevertheless, the asymptotic investigation of this equation is essential for an understanding of why rainbows always appear with the same patterns of intensities and spacings of their bows. (Batterman 2010, pp. 23–24)

The indispensability of these "asymptotic idealizations" lies in the mathematical use of limits "by which various details can be thrown away" (Batterman 2010, p. 23). A de-idealization process would reintegrate these details in the description of the studied phenomenon and we could not explain its stability and regularity. Thus, contrary to Galilean idealizations, such "asymptotic idealizations" are indispensable to the explanation and prediction of phenomena, they do not represent any physical objects, and there is no hope to de-idealize them without loss of explanatory or predictive power.

C4 is similar to Batterman's example, because this boundary condition also implies to consider the limit between wave optics and geometrical optics. If C4 was eliminated, Fresnel's integral could not be solved in Poisson's proof, and the circular screen case could not be identified with an infinitely large opening in Fresnel's proof. If we consider a very large but not infinite opening, the stability and regularity of the bright spot could not have been predicted. Fresnel, for example, emphasizes that his derivation of the bright spot "is independent of the diameter of the screen and of the distance of the light source" (Fresnel 1866, p. 369). Yet, it can only be so because there is no other source of diffraction than the edge of the screen: otherwise, as in the case of the dark spot, the bright spot should occur only at a given distance of the light source. Moreover, colored patterns of diffraction should surround the bright spot. As in Batterman's example, investigating the limit at infinity is essential to predict that the bright spot always emerge with the same pattern. Therefore C4 qualifies as an indispensable asymptotic idealization because it uses the limit at infinity "as a mean by which various details can be thrown away."

4.2 Partially true idealization

But even if C4 cannot be de-idealized, it may still be partially true, because it implies a weaker statement ("the contribution of far away parts of the light wave are *negligible*") which is true.

Uskali Mäki (2011) has argued that apparently false assumptions of what he calls "surrogate models" (models as an indirect way of accessing real targets) can be paraphrased and confirmed. These paraphrases may be worthy of truth nomination and Mäki calls them "truth re-nominations" (Uskali Mäki 2011, p. 219). If the truth re-nomination of an idealization is different from truth only in a negligible way, then it shows that the fictitious idealization was partly true:

> Paraphrases in terms of negligibility and applicability make reference to, and may be true partly in virtue of, properties of the real target system of a model. Thanks to this, they can be used for justifying the original idealization. (Uskali Mäki 2011, p. 231)

In order to justify the boundary condition C4 ("Light infinitely far away from an object is not diffracted") we could then rephrase it with the following proposition:

R The diffraction of the incident wave far away from an object is negligible.

It is true that this paraphrase R shows that idealization C4 is justified, since the contribution of far away part of the light wave to the interference at the center of the shadow is negligible for the experimenter. This paraphrase is empirically testable and is not an “asymptotic idealization” such as C4. However R is not equivalent to C4: actual infinity is not a physical concept that can be tested with measuring instruments. Therefore, if R is true, it does not prove that C4 is true, but only that scientists have no empirical evidence against C4 and may use it in their mathematical treatment of scientific problems.

However, to test R, one needs to study “far field diffraction” (i.e. the behavior of far away parts of the light wave) with Kirchhoff’s diffraction equation,[10] formulated in 1883 (Kirchhoff 1883). R is today considered as the truth content of C4 because we know how to prove—with Kirchhoff’s formula—that, in the bright spot case, far away diffraction is indeed negligible. But when Poisson and Fresnel derived the bright spot phenomenon, there was no guarantee that R would be retained in future theories, and that it was the true part of C4.

Moreover, Saatsi and Vickers show that some boundary conditions of one of Kirchhoff’s prediction in the case of far field diffraction turned out to be “wildly wrong” (Saatsi and Vickers 2011, p. 42). It is then not even sure that R is confirmed by present empirical and theoretical investigations.[11]

In conclusion, R does not show that C4 is true, but that Fresnel’s theory is not incompatible with the truth of the present state of knowledge. If we use the divide et impera move to identify which parts of past theories are compatible with the truth of our present theory of light, it is a valid argument. But then, it is only from the point of view of our present theory of light that we can use this argument. Therefore, as claimed in Sect. 5, only past theories fall within the jurisdiction of the divide et impera move.

4.3 Psillos on idealizations

Psillos proposed his own treatment of idealizations and models (Psillos 2011). Contrary to other philosophers of science, Psillos emphasizes that idealizations cannot be removed or replaced: “try to do without the abstract and the very object of scientific theories—models—disappears too.” (Psillos 2011, p. 17)

Yet, for Psillos, the indispensability of idealizations is compatible with the claim that theories should be understood literally. His argument is based on the explanationist defense of realism and Dummett’s definition of models as “abstract physical objects” (Psillos 2011, p. 4). Psillos’ explanationist defense of realism uses the fol-

[10] Fresnel’s theory is restricted to “near field diffraction”.

[11] In another paper, Vickers suggests that a modern analysis based on Maxwell’s equations can show that it is possible to identify “idle wheels within Kirchhoff’s original boundary conditions”, but “that does not mean that what remains is ‘working’ [i.e. deductively indispensable for the prediction]” (Vickers 2013, p. 207). Therefore, a reformulation of an idealization compatible with our present state of knowledge such as R may not be sufficient to circumscribe the part of this idealization responsible for its success. This opacity of the partial truth of idealizations is discussed in Sect. 5.

lowing *explanatory criterion*: “something is real if its positing plays an indispensable role in the explanation of well-founded phenomena.” (Psillos 2011, p. 15) And for Dummett, models are not fictitious entities but “are linked to the physical world by means of theoretical hypotheses, the generic form of which is: X is—to M, where the solid line is meant to be replaced by a relation of representation (e.g. resemblance or similarity)” (Psillos 2011, p. 9). Models in this sense are surely indispensable tools of the explanation of many phenomena. Therefore, they are real.

The first consequence of this approach is that “the truth of theories does not give them straightforward representational content vis-à-vis the physical world. Their representational content is mediated (at least partly) by abstract objects—the model.” (Psillos 2011, p. 9) The second consequence is that the truth of the model depends on the theoretical laws linking the model to the physical system. Psillos does not consider this issue, because the question he is interested in is about semantics, not epistemology: “what is the world like if a theory is literally understood, that is, if we take it at face value? A literally understood theory need not be a true theory—simply because the world might not co-operate.” (Psillos 2011, note 2)

Therefore, it is possible that the theoretical laws linking a model to a real world system turns out to be rejected by future theories, just as it is possible that the world does no co-operate to make the theory true. For example, Descartes’ astronomical vortex model, which (correctly) predicted the fact that all planets revolve in the same direction around the sun, was later rejected because the law of ‘circular inertia’ (Descartes 1644, book 2, proposition 33) linking the model (a whirlpool) and the physical system (the solar system) was abandoned in posterior theories.[12]

Conversely, if a model still appears to represent a physical system, as it is the case with idealizations C3 and C4, it is only from the point of view of our present state of knowledge. Psillos’ argument does show that idealizations are indispensable to a theory’s success, but do not prove that they should be retained in theory-change because they are indispensable. Therefore, to judge if past idealizations are worthy of belief, it is not sufficient that they fuel a predictive success, but it is also necessary that the theoretical laws linking the idealization to a physical system still belong to our scientific image. If we extrapolate this remark to our present theories, it shows that predictive indispensability is not a criterion powerful enough to circumscribe the true parts of our *present* theories. This claim is developed in the next section.

5 Duhemian realism and the future of science

5.1 The opacity of predictive success

The bright spot case highlights two problems for indispensability arguments based on predictive success and the divide et impera move:

[12] This case is an interesting one for Psillos’ explanationist defense of realism, because in a Newtonian framework, there is no genuine explanation (or prediction) of the fact that all planets move in the same direction. Applying the explanatory criterion, we should then consider that Descartes’ vortex model is real (even if it was latter discarded) because no alternative hypothesis explains this well-founded phenomenon.

– Not all the theoretical constituents retained in theory-change are indispensable to the successful predictions of a theory (Sect. 3);
– Not all the theoretical constituents indispensable to the successful predictions of a theory are clearly worthy of belief: some indispensable idealizations must be de-idealized or rephrased to show that they are compatible with our present theories (Sect. 4).

These two facts do not prove that it is impossible to try to circumscribe the indispensable constituents of a theory's success, nor that it is impossible to prove that past theories successes are compatible with the truth of our theories. But they prove that there is no guarantee that the predictive indispensability of a given part of a theory implies that it is worthy of belief and will be retained in theory-change.

As we have seen in the preceding sections, for the contemporaries of Fresnel's theory, it was not clearly settled which constituents were really indispensable to its predictive success. It was then also difficult to tell which parts of the idealizations needed for this prediction were worthy of belief. This historical fact is what I call here the *opacity* of predictive success for the contemporaries of a theory.

We should then distinguish two uses of predictive success in a defense of scientific realism:

1. The first one is to use the no-miracle argument based on predictive success to circumscribe a set of "mature" theories which can escape the pessimistic induction and be considered as approximately true.
2. The second one is to use indispensability arguments based on predictive success to circumscribe a set of (approximately) true constituents in these mature theories.

The opacity of predictive success does not attack the soundness of the first use but shows that the second one may not be as natural as it looks. Even if we accept that the no-miracle argument can grant (approximate) truth to present theories which have enjoyed predictive success and retained past theories successes, we should be skeptical about which aspects of present theories are true and will reappear in future theories.

5.2 Duhemian realism

If we can assert the (approximate) truth of our present theories but cannot identify which parts of these theories are worthy of belief, does it mean that we should come back to a naive version of scientific realism in which *all* the constituents of our best theories should be considered as (approximately) true?

I claim that it is possible to escape this fate and to be confident in the truth of our present theoretical systems while remaining skeptical about which constituents of these theories are responsible for its success.[13]

[13] I describe this stance as "skeptical" because if we cannot circumscribe which parts of our best theories are true and reflect the basic furniture of nature, then the no-miracle argument is not a sufficient basis for a metaphysical knowledge of unobservables. This view is compatible with Saatsi's version of realism (Saatsi 2015). The "minimal realism" defended by Saatsi claims that there are some *theoretical progresses* through theory-change, but states that we cannot have any *theoretical knowledge* of unobservables. Yet, if we could circumscribe the true parts of present theories, this would grant us theoretical knowledge of these parts.

Such a stance is close to the realist position developed by Duhem in *The Aim and Structure of Physical Theory*. As noted before, Duhem formulated an earlier version of the no-miracle argument based on predictive success at the end of the second chapter of the first part of his book. In this chapter, Duhem argues that the aim of a physical theory is not to *explain* but to *classify* empirical laws. He then asks how can we know whether this classification is natural or artificial, i.e. reflects the real layout of the world:

> If the theory is a purely artificial system, [...] if the theory fails to hint at any reflection of the real relations among invisible realities, we shall think that such a theory will more probably be contradicted than confirmed by a new law. [...]
> If we recognize in the theory a natural classification, if we feel that its principles express profound and real relations among things, we shall not be surprised to see its consequences anticipating experience and stimulating the discovery of new laws. [...]
> And when the experiment is made and confirms the predictions obtained from our theory, we feel strengthened in our conviction that the relations established by our reason among abstract notions truly correspond to relations among things. (Duhem 1914, p. 38)

Duhem's emphasis on the fact that predictions confirm our conviction in the reality of "relations among things" may lead to think that his position is similar to the structural realism developed by Poincaré at the same period. However, for Duhem, this line of reasoning is merely "an act of faith, as incapable of being justified by this analysis as being frustrated by it" (Duhem 1914, p. 36). Therefore, this reasoning cannot be transformed into an indispensability argument. In fact, for Duhem, the structure of physical theories prevents any stable definition of partial truth.

The structure of physical theories is studied in the second part of Duhem's book. It is well known that in chapter 6 Duhem criticizes the idea that "each one of the hypotheses employed in physics can be taken in isolation, checked by experiment, and then, when many varied tests have established its validity, given a definitive place in the system of physics" (Duhem 1914, p. 284). This holistic conception of confirmation implies that no hypothesis of a theoretical system can be said to be definitively indispensable to the prediction of a phenomenon. It is possible to use different sets of hypotheses of the same theory to derive the same result. So one should be skeptical when philosophers or scientists declare that a specific constituent of a theory is true since it is essential to its predictive success. A specific constituent may be essential in one of the possible derivations of this success, but nothing proves that it would be equally essential in another derivation, or that no unconceived alternative derivation may be discovered.

This is why cases such as the two derivations of the bright spot prediction are more common than what appear at first sight. One of the most striking examples is the prediction of Edwin Hubble's relation between the spectral redshift of galaxies

Footnote 13 continued
Therefore, it seems that in order to separate theoretical knowledge from theoretical progress, Saatsi should accept that the criterion to circumscribe the true parts of a theory is only a retrospective one, and therefore cannot be applied to our present theories.

and their distance, confirmed by Hubble's observations in 1929 (although the first researches on the subject were done by Vesto Slipher in the 1910s). This relation was first predicted by the Dutch astronomer Willem De Sitter in 1917 (de Sitter 1917). His model of the universe was based on general relativity, had a constant radius, and a zero density. Ten years later, the Belgian physicist Georges Lemaître, proposed another derivation of the same prediction. His model was also based on general relativity, but it relied on the hypotheses that the density of the universe is not null and that the radius of the universe is increasing with time (Lemaître 1927, p. 49).[14] As in Fresnel's case, two derivations are available in the framework of the same theory—here, general relativity. But each derivation uses different assumptions, equations and idealizations to derive the same phenomenon.[15]

In both cases, we see that using different idealizations as auxiliary hypotheses offers the possibility to unfold different derivations of the same phenomenon. This *local* underdetermination *inside* the framework of a given theory occurs much more often than the empirical underdetermination between two rivals theories. Timothy D. Lyons (2002) and Vickers (2013) provide precious lists of historical examples that the realist ought to consider. In both lists, one can find several cases of alternative derivations of well-established phenomena, such as Dirac's prediction of the positron in 1930, which is based on quantum mechanics but substantially differs from the standard derivation of this particle in modern particle physics. As we saw in Sect. 3, it is possible to try to circumscribe the theoretical constituents common to all these derivations, but we have no guarantee that all possible derivations were taken into account or that these constituents will survive future scientific change.

Duhem's conception of physical theories shows that we can retain the intuition underlying the no-miracle argument and, at the same time, account for the opacity of predictive success. In compressed slogan form, it may be impossible to circumscribe which theoretical hypotheses are worthy of belief without the benefit of the advancement of science because of the way our theories are structured and the way predictions are made, but we can still be (careful) realists and grant approximate truth to scientific theories.

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[14] Lemaître's prediction of the relation between the distance and the redshift of galaxies is not *temporally* novel but can be considered as a *use-novel* prediction for two reasons:

- The equation used by Lemaître to derive this relation has not been designed to accommodate this relation. It was independently discovered by the Russian physicist Alexander Friedmann in 1922, and Friedmann had no interest in the radial velocity of galaxies. His paper is a purely mathematical exercise: it is not even sure that he was aware of the systematic redshifs of galaxies (see (Kragh and Smith 2003) for details). Therefore, the relation between radial velocities and distance is not indispensable to derive the Friedmann-Lemaître equation, which is then used to derive the radial/velocity relation.
- De Sitter's derivation of this relation predicts that there should be some "systematic relation" between the redshift of galaxies and their distance (de Sitter 1917, p. 236). But Lemaître's prediction implies that the relation is *proportional*, which has been observed by Hubble (Hubble 1929).

[15] Another example from relativistic cosmology is the prediction of the cosmological background radiation which was derived first by Alpher and Herman in 1948 on the basis of an isotropic model of the universe (Alpher and Herman 1948), and then by Dicke and Peebles in 1965 on the basis of a non-isotropic but cyclic model of the universe (Dicke et al. 1965, p. 415). The prediction of the existence and position of Neptune was also derived from different working hypotheses by Adam in 1843 and Le Verrier in 1846.

The benefit of adopting Duhem's conception is that we can be confident in the objectivity of our present theories without making future history of science predictable. Even if we grant that our present theories are approximately true, we should acknowledge that the cautious view of the future of science would the following: we can be confident that not *all* of the content of our scientific knowledge (both theoretical and experimental) will be discarded by future scientific revolutions. We can also be sure that *some* constituents of this knowledge will be completely transformed. But we do not know which constituents will be eliminated and which will be conserved.

If some laws (such as Moore's law) seem to predict more or less precisely technological evolution, no law has ever been able to predict theoretical changes. History of science is a succession of surprises and we cannot even be sure that future theories will be formulated in the same mathematical and logical canvas as our present theories.

Yet, if we could use the divide et impera move as an indispensability argument to determine which constituents of our present theories are true, then we would be sure that these constituents will be retained in future theories. Therefore, these future theories would be partially predictable. This is why the divide et impera move's jurisdiction should be restricted to past theories and not be used as an indispensability argument to prove that some parts of our present theories are worthy of belief.

Note that if the divide et impera move has only a retrospective use, nothing warrants that hypotheses now considered as the true parts of past theories will still be compatible with superseding theories and regarded as true in the future. Reciprocally, abandoned parts of past theories or discarded research programs might be revived by future scientific revolutions. In biology, for example, epigenetic theories of heredity have been interpreted as a revival of Lamarck's theory of the inheritance.[16] Even seemingly solved case of underdetermination can resurface. For example, after Arago and Foucault's crucial experiment in 1850 (the measurement of the speed of light in water), it was widely believed that light was truly undulatory and that the underdetermination between corpsucular and undulatory theories of light was solved. But with Einstein's study of the photoelectric effect in 1905, corpuscular aspects of light were reintegrated to our modern scientific image.

6 Conclusion

In this paper, I have studied the definition of partial truth based on the divide et impera move and predictive indispensability. The conclusion is that the criterion to circumscribe the true parts of a theory can be defined only from the point of view of superseding theories.

Other suggestions as how to account for partial truth which do not rely on indispensability arguments—such as Anjan Chakravartty's distinction between "auxiliary properties" and "detection properties" (Chakravartty 2007, p. 30)—exist on the market. However, one of the lessons of the bright spot case concerns all the attempts to

[16] I am thankful to an anonymous reviewer's suggestion for this example.

account for partial truth: such accounts must not make the future of science predictable and therefore should not rely on a prospective (but only retrospective) criterion to circumscribe true theoretical hypotheses. As Duhem puts it, examples from history of science "should show that it is very imprudent for us to say concerning a hypothesis commonly accepted today: 'We are certain that we shall never be led to abandon it because of a new experiment, no matter how precise it is'" (Duhem 1914, p. 323). Our conceptions of scientific realism should reflect this fact.

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Appendix: The derivation of the bright spot from Fresnel's integral

This appendix shows how to derive the bright spot prediction form Fresnel's integral with mathematical tools available at the beginning of the nineteenth century. This derivation can be found in a classical textbook of optics (Moeller 2007, p. 133). Let's apply Kirchhoff–Fresnel's integral to compute the amplitude u of the light wave at the center of the shadow of a circular screen:

$$u = A2\pi\rho_0 \int_{\sqrt{a^2+\rho_0^2}}^{\infty} \left(\frac{1}{\rho^2}\right) e^{ik2\rho} d\rho \tag{1}$$

In this formula, u is the amplitude of the wave at the center of the shadow, A the amplitude of the incident wave at the source and a is the radius of the circular object. ρ is the distance between the diffracted wave and the center of the shadow, ρ_0 is the distance between the center of the circular object and the center of the shadow (see Fig. 1). Then, $\sqrt{a^2 + \rho_0^2}$ is the distance between the edge of the circular object and the center of its shadow. Thus, the integral (1) represents the contribution of all the diffracted light wave at the "optical center" of the screen, i.e. the center of the shadow.

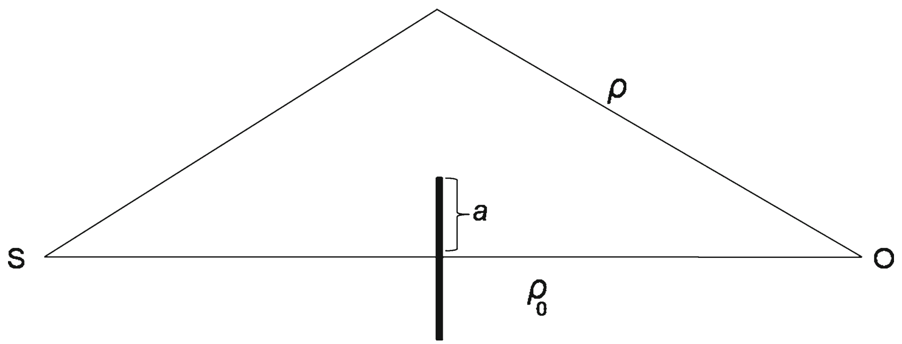

Fig. 1 Diffraction by a circular screen. *S* source of light, *O* center of the shadow

Integration by parts of (1) yields:

$$u = \left[\left(\frac{1}{\rho^2} \right) \left(\frac{1}{2ik} \right) e^{ik2\rho} \right]_{\sqrt{a^2+\rho_0^2}}^{\infty} + (1/ik) \int_{\sqrt{a^2+\rho_0^2}}^{\infty} \left(\frac{1}{\rho^3} \right) e^{ik2\rho} d\rho \tag{2}$$

Neglecting the right part as null gives:

$$u = \left[\left(\frac{1}{\rho^2} \right) \left(\frac{1}{2ik} \right) e^{ik2\rho} \right]_{\sqrt{a^2+\rho_0^2}}^{\infty} \tag{3}$$

To solve this equation, we have to assume that at infinity, the light wave is not diffracted, i.e. that rays infinitely far away from the screen have a null contribution to the constructive interference at the center of the shadow. Then, to compute the intensity, we use the relation: $I = uu^*$ If we pose that: $I_0 = A^2 \frac{\rho_0^2}{\sqrt{a^2+\rho_0^2}}$, then (3) gives:

$$I = \frac{I_0 \lambda^2}{4} \tag{4}$$

The intensity I thus only depends on the wavelength and is proportional to $I_0/4$ for a given wavelength. This results corresponds to the intensity in the absence of any obstacle, which means that the center of the shadow is illuminated as if there was no circular object.

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