Energy flow lines as light paths: a didactical analysis

Energiestromlinien als Lichtwege: Eine didaktische Analyse

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Abstract
Analyses of interviews with secondary school students about their conceptions of light at the University of Potsdam indicate that numerous students have a deterministic view of light. With regard to these results the model of energy flow lines, which has been discussed recently in the didactical literature, is of special interest. Following this model, light is presumed to move along energy flow lines as trajectories.

In an analysis of the model of energy flow lines four didactical dimensions (didactical content, internal structure, present-day relevance and future significance) are investigated. It can be shown that a discussion of this model in physics at school can increase the meta-conceptual knowledge of the students about the models of light. On the other hand, this can promote deterministic conceptions and the Bohm interpretation of quantum mechanics. But the question remains: Should the nature of light really be described as deterministic?

Kurzfassung
Die Auswertung von Schülerinterviews zu den Modellvorstellungen des Lichts, die an der Universität Potsdam durchgeführt wurde, zeigt, dass zahlreiche Schülerinnen und Schüler eine deterministische Vorstellung zum Licht besitzen. Unter Bezug auf diesen Befund ist das Modell der Energiestromlinien, das in den letzten Jahren in der Literatur diskutiert wurde, von besonderem Interesse. Im Rahmen dieses Modells werden die Energiestromlinien als Trajektorien betrachtet, denen das Licht folgt.

Diese Modellvorstellung wird hinsichtlich der vier Zieldimensionen (Gehalt, innere Struktur, Gegenwartsbedeutung und Zukunftsbedeutung aus Sicht der Lernenden) didaktisch analysiert. Es zeigt sich, dass eine fundierte Behandlung im Physikunterricht einerseits das metakonzeptuelle Verständnis für Lichtmodelle fördern kann, andererseits Vorstellungen in Sinne einer Bohmschen Deutung der Quantenmechanik induziert werden. Letztendlich stellt sich die Frage: Soll das Verhalten des Lichtes tatsächlich als deterministisch dargestellt werden?

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1. Models of light

When investigating and discussing the nature of light students in school, college and university are confronted with numerous models. Among other models, light can be treated in the context of the ray model, the wave model, the phasor model, the Newtonian particle model and the quantum model.

In addition to these models, the model of energy flow lines was suggested and intensely discussed in literature (Wünscher et al. 2002) recently. Some consequences of the use of this model of light at school will subsequently be presented in this paper.

2. Student conceptions of light

Physics education research at the University of Potsdam has shown that using a plenitude of different models in school can lead to numerous severe complications at the process of model construction of students (Mikelskis et al. 2002). Especially in optics, the students investigated often show a tendency to construct hybrid models. In their descriptions, an appropriate and necessary distinction between different models of light is lacking (Horn et al. 2002).

In addition, students prefer descriptions of optical processes using the ray model with clearly predetermined light paths.

Student 1: „I always imagine photons as small particles, which are just quanta going straight through the slit. And maybe, they slightly hit the upper edge of the slit and maybe, they are therefore slightly deflected from their straight flight path.”

Student 2: „It will of course be especially simple if you imagine light as small particles. (...) There the properties of particles are inherent, and they then propagate in the form of waves.”

Abb. 1: Äußerungen von Schülern aus Physik-Leistungskursen (13. Jg.) zur Natur des Lichts.

Dieser deterministische Grundhaltung ist in Schüleräußerungen durch die Zuordnung von Teilchenbahnen (siehe Abbildung 1) explizit erkennbar. Der weitaus größte Teil der Schülerinnen und Schüler folgt dieser lebensweltlich begründeten Einstellung.

Die große Attraktivität dieses Konzepts zeigt sich auch durch eine hohe Bereitschaft der Schülerinnen und Schüler, Hybridkonzepte des Lichts zu konstruieren, in denen Bahnen oder Bewegungsrichtungen als wesentlicher Bestandteil enthalten sind. Die Be-
sscription of sinusoidal trajectories of light particles is a typical example of this process.

3. The model of energy flow lines

Models of light which support a deterministic tracking of light paths, particularly accommodate these student conceptions. The model of energy flow lines is one of these student-friendly models.

Energy flow lines technically describe the transport of energy of light from light sources to absorbers. They never cross. Therefore energy flow lines behave in a similar way to field lines of electric or magnetic fields. These characteristic properties of energy flow lines are demonstrated in figure 2 in the example of an arrangement of mirrors.

Deutlich sind die Unterschiede im Vergleich zum Verhalten von Lichtstrahlen sichtbar:

- Die Trajektorien des Lichts verlaufen parallel zur Spiegeloberfläche M. Nur eine Trajektorie verläuft in unmittelbarer Nähe der Spiegeloberfläche. Die anderen Trajektorien des restlichen Lichts unterliegen einer spukhaften Fernwirkung.
- Da sich die Trajektorien nicht überschneiden dürfen, gelingt nur der unteren Hälfte des Lichtbündels, das auf den schräg platzierten, halbdurchlässigen Spiegel trifft, eine Transmission. Die obere Hälfte des Lichtbündels wird weit vor dem halbdurchlässigen Spiegel nach oben abgelenkt.
- If both pencils of light hit each other again, they will not cross. They will instead be deflected in a region of interaction (see the top right corner of figure 2).

Consequently the light paths of this model construction run in a similar way to the light paths of deterministic quantum mechanics proposed by David Bohm (Bohm & Hiley 1993):

- In the Bohm approach at an infinite high potential barrier the trajectories of quantum objects (like photons or electrons) also largely run parallel to the surface structure of the potential barrier.
- At a finite potential barrier only the light which hits the potential barrier first can penetrate the barrier. The light hitting the potential barrier later is deflected.
- In the region of interaction the Bohm trajectories do not cross (Hiley et al. 2000a, 2000b). They also behave in analogy to figure 2. According to the Bohm interpretation light being detected by a detector at the top of the interaction region unambiguously comes from the left. A detector situated at the right of the interaction region according to Bohm detects only the light which comes from below – provided the light is coherent.

4. Didactical consequences
The interpretation of optical effects using the concept of energy flow plays an important part in the area of non imaging optics. Wünscher et al. (2002) discuss numerous practical examples of that. The physical content of this interpretation therefore is high.

Similarly interesting is the epistemological content. Models and theories in physics are free inventions of the human mind (Poincaré 1905). They can therefore be neither false nor correct. Because of that Wünscher et al. argue that energy flow lines can be interpreted as trajectories and as strictly predetermined paths of light.

The internal structure of the energy flow line approach closely follows the structure of electrostatics, and at school numerous field line pictures of electrostatic and magnetostatic situations are discussed. Following Wünscher et al. these can be taken as an introduction to the topic of the energy flow of light.

However the present-day relevance students may assign to a deterministic model of light is didactically problematic. The use of energy flow lines to illustrate optical situations at school can intensify and strengthen the naïve conceptions of students mentioned above. An analysis of these conceptions
at the University of Potsdam showed that only a minority of students has a meta-conceptual understanding of models. And only this minority of students is able to distinguish precisely between different models and between reality and the world of models.

Without model-oriented lessons aiming to develop and to strengthen the meta-conceptual abilities of students, the presentation of deterministic light models at school can reinforce their naïve conceptions of light. Thus the model of energy flow lines can only be one of many models discussed in physics lessons. All these models should be strictly distinguished from one another.

Indeed, the future significance of the model of energy flow lines is very questionable. This model can be understood as leading directly to deterministic quantum mechanics. In fact, after discussing the model of energy flow lines at school, the students may comprehend Bohm trajectories easily but these exist only if the light is coherent.

Two non-coherent pencils of light do not interact and cross each other undisturbed (Hiley et al. 2002a). An explanation of this undisturbed penetration of light will then be a considerable didactical problem if later interference is introduced and if students are cognitively fixed upon energy flow lines.

5. Concluding remarks

Shall we promote a way of teaching physics which aims at a strictly deterministic vision of the world? Or a strictly stochastic one? Bohm quantum mechanics – in my very personal opinion – seems to be mathematically an awkward and structurally an unwieldy theory. Yet how should learners recognize the beautiful and practical if they have not experienced the ugly and unpractical?

The characterisation of energy flow lines as light paths leads didactically straight to the Bohm interpretation of quantum mechanics. Whether through a discussion of energy flow lines of light one can work towards this model in school or avoid or pass is over is ultimately left up to the teacher. For not only are models in physics neither true nor false and a pure invention of the human mind: this is all the more so in the case of didactical models.

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Attachment
The following energy flow line pictures were presented at the poster session of the GDCP annual conference in Heidelberg. They were constructed with Lightlab (Software archive Karlsruhe 2002).

Anhang
Auf der GDCP-Jahrestagung in Heidelberg wurden auch die folgenden mit Lightlab (Karlsruher Software-Archiv 2002) konstruierten Energiestromlinienbilder vorgestellt.

Figure 3 / Abbildung 3

Figure 4 / Abbildung 4
Fig. 3 – Fig. 6: Energy flow lines which behave in a similar way to field lines of electric or magnetic fields.

Abb. 3 – Abb. 6: Energiesstromlinien in Anlehnung an Feldlinienbilder der Elektrostatik und der Magnetostatik.

A \hspace{1cm} L \hspace{1cm} WS

absorber \hspace{1cm} Lambertian light source \hspace{1cm} white scattering surface (perfect white wall)

Absorberoberfläche \hspace{1cm} Lambertscher Strahler \hspace{1cm} diffus streuende Oberfläche (perfekte weiße Wand)

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