To my scientific sparring partners
Bill Doyle, Alistair Fraser, and Akhlesh Lakhtakia
Craig F. Bohren

To my father and mother,
they always choose kindness and curiosity over fixed notions;
to my brothers and sisters,
for sharing the wild ride;
to Jessica,
for her enduring patience and relentless support,
and to our sons Daniel and Joshua,
that they grow in the generosity of spirit of their
grandmothers and grandfathers.
Eugene E. Clothiaux

Contents

Fundamentals of Atmospheric Radiation: An Introduction with 400 Problems. Craig F. Bohren and Eugene E. Clothiaux

ISBN: 3-527-40503-8

Preface

Like so many textbooks, this one has its origins in the classroom, the fruit of more than 30 years of combined experience teaching courses on atmospheric radiation to graduate and undergraduate students of meteorology. This experience has forced us to recognize that most of our students do not adequately understand the fundamentals of electromagnetic radiation and its interaction with matter. Students come to the classroom with their heads full of mantras, half-truths, or outright errors, and much of our effort has been devoted to trying to convince them that what they think are universal truths are at best approximations or simply wrong. Indeed, all theories are ultimately wrong. And a theory is just scribbles on paper, not reality. Theories can help make sense of reality but they are not reality itself.

We are careful to expose to the clear light of day all assumptions underlying theories, their limitations and ranges of validity. Nothing is intentionally swept under the rug. Because all theories ultimately break down, you must know what underlies them to have a hope of fixing them when they do. Ignorance is not bliss.

James D. Patterson, a retired physics professor, published An Open Letter to the Next Generation in the July 2004 issue of *Physics Today*. This letter is charming and refreshingly honest. Patterson does not brag about his triumphs but instead warns the next generation about mistakes he made in his career. He notes that, "We have to learn basics first, because we need them for all that follows. If we do not learn the basics, we are disadvantaged. A related sin is skipping essential details. Then we do not get to the bottom of things and are not well grounded."

Many of the references at the ends of chapters are to original papers. Again, we quote Patterson: "When we want to know something, there is a tendency to seek a quick answer in a textbook. This often works, but we need to get in the habit of looking at original papers. Textbooks are often abbreviated, second- or third-hand distortions of the facts, and they usually do not convey the flavor of scientific research." We go even further than Patterson and note that whenever you see in a textbook a statement of the form "Einstein [or Newton or some other scientific worthy] said..." replace "said" with "did not say" and what follows is more likely to be true. Even direct quotations are not reliable because so often textbook writers can't be bothered to go to the library (too far to walk) and so pass on what they think they remember that some other textbook writer thinks Einstein (or whoever) might have said. The only sure way to find out what our predecessors said is to read their own words.

We present theories as a hierarchy, each level of which is more encompassing than its predecessors but each correct subject to stated limitations and approximations. Learn at a certain level secure in the knowledge that what you learn need not be unlearned. To go on to the next level is for you to decide. For example, Chapter 5 introduces multiple scattering by

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way of a pile of plates, which can be used to illustrate much of the physics of more complicated multiple-scattering media, such as clouds, and also is a way of introducing concepts and terms in more advanced theories. But there is nothing to be unlearned because what we say is true, subject, as always, to the stated limitations of the theory. You can then move on to the two-stream theory from which you can acquire much of the physical intuition you need to understand multiple scattering. If you wish, you can stop at the end of Chapter 5. You will have mastered something complete unto itself but not the final word (there is no final word). You need not feel ashamed for not knowing the supposedly exact (nothing is exact) equation of radiative transfer or how to solve it. There are plenty of folks who can crunch numbers using this equation but don't understand them or lack the ability to estimate them without resorting to extensive calculations (using someone else's data in someone else's computer program). Even a superficial reading of the history of science conveys the lesson that the best scientists have superb intuition. The number crunchers and formalists occupy the lower ranks. This is even true of mathematicians, who are mistakenly looked upon as logic machines. The good ones know in their bellies what is true. Proofs are needed mostly to convince others. Today, many mathematicians make their livings proving or attempting to prove the conjectures (i.e., flashes of mathematical insights) of their illustrious predecessors.

Understanding should come before number-crunching. Our aim is to give you an intuitive feel for the subject matter, a firm grasp of its foundations, and to show how theories help you understand observations and measurements. Again, Patterson's lament is apposite: "I had been more interested in getting good grades than gaining understanding".

Nowhere in this book will you find condescending and insulting statements of the form "it is trivial to show". Nothing is trivial. We had to work hard for every equation, often arguing for days about "trivial" points. The deeper you delve into a subject, the more subtleties you uncover.

It seems that textbooks are almost required by law to be boring, to be carefully purged of all traces of their human authorship. We occasionally break this law. We tell stories. Some may make you laugh. Others may make you mad (and they certainly will make your professors mad). A word of caution: Peter Pilewskie read some of the first drafts of this book, and told us that he had to be careful not to drink anything while reading because while drinking a soda he happened upon a passage that caused him to convulse with laughter and spew soda over himself and his surroundings.

In an ideal world we'd like this book to read like a racy novel. But even if we were capable of writing one, it would no doubt attract the scorn of what Sinclair Lewis in *Arrowsmith* called "Men of Measured Merriment", by whom we do not mean editors. Our experience has been that the blame for dry, lifeless textbooks lies with their authors, not with censorious and humorless editors. There is a strong sentiment within science that it should be a grim grind, that if you enjoy doing it you are not really working. Many years ago the senior author was a visitor at a university that shall remain nameless. At the time he was working long hours, seven days a week. One day, out of the blue, a red-faced professor marched into his office and blurted, "You! You think you work so hard. You don't work hard because you *enjoy* what you are doing." He was serious. This was no joke. The senior author also was attacked on the floor of the United States House of Representatives because of an article in the *National Enquirer* in which he was quoted as saying that he was having great fun doing research on

green thunderstorms. It seems that if you take money from the government for doing research you shouldn't enjoy it (or if you do, pretend that it is disagreeable).

We are much more critical of demonstrable nonsense than is the norm, or even permitted, in textbooks. We reckon that there is a statute of limitations for forgiving textbook writers for errors. When books contain statements that have been known to be false for 50 or 100 years, the time has come to heap ridicule on the heads of those who continue to propagate them. For example, there is no excuse, nor has there been for about 100 years, for continuing to say that the refractive index must be greater than 1 or that there is any necessary relationship between density (mass or number) and refractive index.

In the second volume of his *Recuerdos de mi Vida*, the histologist Santiago Ramón y Cajal notes with some acerbity that "In contrast to shameful custom, the child of traditional laziness, my book was to contain, as solemnly promised in the preface, only original illustrations and conclusions drawn from my own investigations." Although we can't promise that all conclusions in this book are drawn from our own investigations, we can promise that our illustrations are original. We did not write with scissors and paste. We made many measurements solely for this book and designed figures intended to convey ideas as clearly as possible. The instrument used for all spectral measurements was a Photo Research SpectraColorimeter Model PR-650 SpectraScan, which measures radiation from 380 nm to 780 nm in increments of 4 nm with a bandwidth of 8 nm.

We hereby declare this book to be an acronym-free zone. To the extent possible we use no acronyms. They are the bane of scientific writing, making it even more boring and arcane than it would be otherwise. The anonymous author of an article in the April 16, 2005 *Economist* comments on the "delight in creating forced acronyms that plagues many branches of science." A plague acronyms indeed are, and claims that they save space are laughable given that acronym-mongers are invariably sloppy writers who could save much more space by writing more compact sentences. But aside from their ugliness, acronyms are just one more way of creating barriers between those who are in the know and those who are not, cabalistic symbols by which the initiated recognize each other. We are waiting to see a paper (maybe it already has been published) entitled "The effect of SSTs on SSTs."

Wherever possible we give the full names of authors of papers and books we cite. Most scientists do have first names, despite efforts to conceal them, and it is rumored that some even have mothers and fathers. We also spell out in full the titles of journals. Cryptic abbreviations, like acronyms, are yet another way of distinguishing between the in-group and the out-group. Do you know what MNRAS stands for? If not, you are a barbarian, not fit to eat at the same table with the lords of the universe.

A book is supposed to be a conversation between authors and readers. The best way to converse with us is to work the problems. There are almost 400. They are not acts of penance but give you the opportunity to test your mastery of the subject matter (memorization of formulas is not mastery) and they expand on topics touched on briefly if at all in the bodies of the chapters. Many of these problems are questions asked by students or correspondents. We enjoyed answering them. And if you don't enjoy solving problems, you might ask yourself why you are studying science. Scientists solve problems. So get to work. And enjoy yourselves (but frown a lot so that no one will know).

Acknowledgments

Acknowledgements are always problematical because much of what one learns comes not from books and papers but from casual conversations, often in convivial surroundings. More than 25 years ago I spent over a year in the Institute of Atmospheric Physics at the University of Arizona. At the end of each day, Sean Twomey and I, sometimes accompanied by Don Huffman and Phil Krider, would march off to the nearest tavern for a few beers. Although some of our conversation centered on horse racing, Sean's great passion, we also discussed science at length. A year spent in a barroom with Sean Twomey is equivalent to a graduate degree in atmospheric science. I do recall that one topic in this book stems from a story he told me. When he worked for the Commonwealth Scientific and Industrial Research Organization in Australia, manuscripts had to be reviewed by scientists in a division other than that from which the manuscripts originated. Sean blasted a manuscript by a radio astronomer who had committed the blunder of assuming that the sum of exponentials is an exponential. The fuming author called Sean and asked him angrily, "What the hell do you know about radio astronomy?" Sean replied, "Nothing, but I do know something about exponentials."

But my memory is becoming less reliable as I make the inevitable descent into senescence. As the story of the exponentials demonstrates I can remember almost the exact date and place where I acquired some pearls of wisdom, while others are lost in a haze. I neatly handled the problem of acknowledging three colleagues, Bill Doyle, Alistair Fraser, and Akhlesh Lakhtakia, by simply dedicating this book to them. Bill and Akhlesh have been and continue to be my sounding boards on electromagnetic theory. Both have an encyclopedic knowledge of the subject, including its history, and are aware of the many subtleties that don't make their way into textbooks. Although Bill is approaching his 80^{th} year he still retains the enthusiasm one hopes to see in college freshmen. We continue to correspond and talk on the telephone, although now he has to call me at night to spare his office mate from having to listen to our raucous conversations. Akhlesh and I have lunch every few months and call each other with questions at all hours of the day and night.

Alistair Fraser made my 20 years at Penn State a rewarding and fruitful experience. Without him I might not have stayed. Much of what I know about atmospheric optics I learned directly from him or honed what I already knew (or thought I knew). Had it not been for Alistair my academic career almost certainly would have been different. Having such a brilliant scholar and inspiring teacher to work with made it almost inevitable that I would join forces with him. I followed in his footsteps by teaching a unique course of his design, meteorological observations, in which students photograph optical phenomena in the atmosphere and write reports on them. This is the one course that indelibly changes students. They are never the same going out as coming in. And the same can be said about the teacher. Our students were often amazed at how severely Alistair and I criticized each other. We had to explain to them that this was the best way of ensuring that our work was of the highest quality. Alistair is quick to spot logical flaws, a merciless critic of sloppy exposition, a superb interpreter of what can be seen with the naked eye.

At Penn State I also had the good fortune to learn from Herschel Leibowitz, one of the most eminent perceptual psychologists, who would teach me at the breakfast table what physicists should know, but usually don't, about how humans construct a visual world out of raw optical data.

Thanks also to Paul Kay for his criticism of our discussion of color words.

More than 30 years ago my first teacher of radiative transfer was Bruce Barkstrom with whom I collaborated on a paper on radiative transfer in snow on the ground. This was a fruitful and enjoyable collaboration that brought me up to speed on much of what I needed to know.

Although Don Huffman did not contribute directly to this book, other than to provide me with a few references, his lasting influence can be felt on everything I do.

For many years I have corresponded with Warren Wiscombe, who fires questions at me every few months, causing me to refine ideas and correct errors. And this even before email made correspondence much easier.

Ray Shaw was a guiding force behind the discussion of nonexponential attenuation in Chapter 2. Thanks also to Joe Shaw for sending me reprints and to Glenn Shaw for siring Ray and Joe.

Tim Kane directed us to references on optical heterodyning.

If computers and their programs can be "user-friendly", users should have the right to be "computer-unfriendly". As my colleagues know, I am outright computer-hostile. But I am grateful to Harry Henderson and Chuck Pavolski, who responded speedily and graciously to my anguished and profane cries for help when my computers, no doubt sensing my hostility toward them, rebelled against my authority.

To save Tom Kozo possible embarrassment I won't say what he contributed, but he knows.

Manfred Wendisch had the most direct effect on this book. We sent him the first versions of most of the chapters, which he went over with a fine-tooth comb, saving us from many errors, causing us to tidy up terminology and tighten our arguments. He also caused us to take more care to make this book understandable to people whose first language is not English.

Peter Pilewskie critically commented on early versions and independently checked some of our at-first puzzling Monte Carlo calculations in Chapter 6. He also generously allowed us to publish some of his measurements, the only ones in this book we did not make.

When I had some tricky (for me) mathematical questions I turned, as usual, to George Greaves, my former climbing partner, companion on many ascents, some hair-raising, in Iceland and Scotland many years ago.

Others who contributed to this book, if only indirectly by way of the residue of mostly forgotten conversations, are Tom Ackerman, Rich Bevilacqua, Ted Staskiewicz, Tim Nevitt, Cliff Dungey, Raymond Lee, Phil Krider, John Olivero, Denny Thomson, Shermila Singham Carl Ribbing, Larry Woolf, Andy Young, Claes Beckman, Günther Können, Ken Sassen, Dick Bartels, and Fred Loxsom.

Because of my popular science books and writings on atmospheric optics, hardly a week goes by that I don't receive email from someone, somewhere in the world, from senior scientists to elementary school students, asking me questions some of which made their way into this book. To this anonymous army of inquisitive people I am also grateful.

My many students contributed questions, which I tried to answer, and misconceptions, which I tried to dispel. At least half of the problems in this book were taken from examinations and homework problems.

The portable spectrophotometer used for the spectral measurements in this book was purchased through a grant from the National Science Foundation with matching funds from the Penn State University Department of Meteorology.

To date I have written books with three collaborators, with whom I am still friends. So although I am not easy to work with, I am not impossible. Eugene Clothiaux had the hardest row to hoe of all my collaborators. I depended on him for all the heavy work that I am no longer capable of doing. All this while he was struggling up the academic ladder and helping to raise young children. Aside from the intellectual burdens of collaboration, Eugene bore physical burdens that are perhaps unusual. Because I am retired Eugene had to make the trek to my house frequently, carrying books and papers and the latest versions of chapters. His ancient car could not make it all the way up our steep and rutted road (which he calls "the creek bed"), so in all kinds of nasty weather he would park at the house of our neighbors, then trudge up the last quarter-mile, in winter a veritable ice sheet. Now that's dedication!

As usual, my most heartfelt thanks go to Nanette Malott Bohren, my companion of more than 40 years, who had to put up with the mess and stress of yet another book but who carefully pored over draft versions ferreting out logical and typographical errors. Although Nanette has no formal scientific training, she has the amazing ability to spot errors in equations and inconsistent notation.

Craig F. Bohren
Tŷ'n y Coed
Oak Hall, Pennsylvania
July, 2005

My fortune is great in having grown up in the late twentieth century United States. Those Americans living two generations back provided the infrastructure and support that allowed my father to earn a doctorate in physics and my mother a doctorate in math and science education, even though higher education was totally lacking in their families. For a mere $4,000 of my parent's money I was able to study with Jean-Marie Wersinger, George Kozlowski, Charles Brown, Delos McKown and my father at Auburn University as an undergraduate in physics. I was able to parlay this initial investment into a graduate assistantship with Leon Cooper, Mark Bear and Ford Ebner in physics and neural science at Brown University. My luck continued into the 1990s when I received a postdoctoral research fellowship to work with Tom Ackerman, Bruce Albrecht and Denny Thomson at Penn State University. During my years as a research associate and assistant professor at Penn State University, faculty members of the Department of Meteorology were incredibly supportive, to a degree so great that I have dubbed this faculty as King Arthur's Court.

The field of atmospheric radiation is full of feisty, but kind, characters. In all of his years of research in this field Warren Wiscombe has encountered only two scientists whom he has described to me as not only feisty but also a bit nasty. Such individuals are rare in the field of atmospheric radiation and I have yet to meet them – maybe I never will. I view my colleagues much like Klaus Pfeilsticker describes his colleagues in Boulder, Colorado – as his "Boulder Family." I have my ARM Science Team Family, my MISR Science Team Family, my European Union CLOUDMAP2 Family, my Family of Wonderful Graduate Students and my Fellow Members of King Arthur's Court. I have learned, and continue to learn, a tremendous amount from all of these colleagues.

Howard Barker has influenced my thinking about many topics in this book. Ideas from Mark Miller, Pavlos Kollias, and Roger Marchand have no doubt found their way into this book. Tony Clough, during a series of enjoyable dinners dating back to the mid-1990s, has tried time and again to straighten out my thinking on topics in Chapter 2, and I am not sure I have them all straight yet. But I am certain that his and Eli Mlawer's assistance over the years has provided me the best chance of properly running their line-by-line radiative transfer model and monochromatic radiative transfer model, which we used to generate all of the high spectral resolution figures in this book. Rich Bevilacqua provided timely insights to us on retrieving water vapor profiles in the mesosphere at microwave frequencies. I first learned some Monte Carlo methods from Tom Ackerman in the early 1990s, and the first code that I ever used that could be started on one machine and then replicate itself to run on many machines was developed in a collaboration between Elizabeth Post and Tom. In the years since I have learned a great deal from Sasha Marshak (who has devoted time and patience to his many discussions with me), Anthony Davis and Frank Evans about radiative transfer in general and Monte Carlo techniques in particular. Elizabeth Post's original code has undergone radical changes as a result but she would nonetheless recognize the code that remains to this day. Discussions with Qilong Min motivated specific applications in Chapter 6. Of the graduate students I worked with at Penn State those who made a direct contribution to the radiative transfer codes I used for this book include Chuck Pavloski, Seiji Kato, Laura Hinkelman, Daniel Pawlak, Jason Cole and Jonathan Petters. All of the Monte Carlo terrestrial radiation calculations for Chapter 6 were produced by Jason Cole with a Monte Carlo code that he developed during his thesis research. Those with indirect contributions to topics in this book include Jay Mace, Chuck Long, Jim Mather, Andy Vogelmann, Ruei-Fong Lin, Xiquan Dong, Michael Jensen, Urszula Jambor, Adrian George, Kim Fineran, Manajit Sengupta, Greg Schuster and Dave Groff. Students in the atmospheric radiation courses that I taught always provided valuable feedback, with Kelly Cherrey and Jesse Stone's comments being of particular value as this book project came to an end.

For ten of my fourteen years at Penn State I had no idea who Michael Modest was even though I can see his office window from mine. He contributed ideas to Daniel Pawlak and Jason Cole during their study of radiative transfer.

I have never met our editors and technical assistants at Wiley-VCH in Germany – we did everything by email. Nevertheless, their support was wonderful. Andreas Thoss helped us in the early stages and Ulrike Werner helped us reach the end. Uwe Krieg always provided timely support with the Wiley-VCH LaTeX style sheets. I would send emails to them at the end of the day and without exception I would have my answers the following morning. They gave Craig wide latitude in determining the style of this book. After we had missed our third (or was it fourth?) deadline Ulrike told me not to worry, that if I had known what I was getting myself into with the start of this book I never would have done it. She was right, and her patience made ending this book project as pleasant as it could be. While our Wiley-VCH editors took care of our book business, Patrick Cleary's skill, flexibility, and open-mindedness was wonderful on my home front.

I owe a special thanks to Tom Ackerman and my co-author. Over the years I have learned more about atmospheric radiation from these two scientists than from any other person. My hope throughout the 1990s was that Tom and Craig would write a textbook and include me as a co-author if I could perform enough work on their behalf. Such a book might be dubbed

the ABCs of atmospheric radiation, or the BAC of atmospheric radiation, but certainly not the CAB of atmospheric radiation. When Alistair Fraser suddenly retired and disappeared from Penn State University in 2001, Craig, a bit rattled from Alistair's departure, asked me to help him write a textbook in which he organized his diverse thoughts and scattered writings on atmospheric radiation. I asked him if I could get Tom to help us out. He said no – that Tom and he would have too many difficulties reaching agreement on content and style throughout the book. When I asked Tom the same question, he agreed with Craig. My hopes went up in smoke. I very much wanted to help Craig but I could not do so without Tom's blessing. I knew that whatever ideas of mine got into a textbook would partly be Tom's. Tom, as always, was amazingly gracious. He told me that I should help Craig and that I should have no worries about ideas of his that got into the book via my contributions. Over the nine years that I worked with Tom his boundless generosity towards me and the fantastic graduate students that he recruited was truly remarkable. He is second to none in this regard. I was indeed fortunate when I first crossed Tom's path in the pastry queue on the Sunday morning of April 21, 1991, during the American Institute of Physics symposium "Global Warming: Physics and Facts" held at Georgetown University.

Craig Bohren lives in a different world from the rest of us. During the course of writing this book, he has received hundreds, if not thousands, of emails from people with no real experience in science, or a bit of informal training, or plenty, or even experts in this field and that. To the best of my knowledge he has answered many, perhaps most if not all, of these emails as he tries to bring understanding to the people who write to him. My guess is that this diversity of his experience over many years has contributed to his strong and forceful statements in his discourse on science. Time and again he has energetically criticized me for writing paragraphs that he describes as incomprehensible. On a day close to the completion of this book, he called me and told me that what I had sent to him made him truly depressed – what I wrote was not clear and he could not make sense of it and it was depressing him to no end. As despair began to sink into me, I had to remember that this was Craig and he takes science communication seriously. He was being blunt because things were not clear to him and he wanted to make them clear. Over the next week he pursued cleaning up my ideas with such vigor. As he put ideas together in a logical and consistent manner I could see his mood lighten and his excitement grow. To me this is quintessential Craig – vigorously criticizing someone, me in this case, to educate as he gains clarity on a topic himself. I have come to appreciate to no end this intellectual sincerity on the part of Craig.

So, when Craig criticizes with passion something or someone in our text, he is doing so to make a point and not to humiliate. Ironically, I know that one of the first people most likely to find shortcomings in our text is going to be Tom Ackerman. I look forward to discussions with Tom in regards to aspects of the text because I know that he will be conversing with me to express his thoughts regarding some point here or there and to educate me as well. My hope is that when my colleagues, other scientists and students find an error they also let me know about it in the spirit of Tom.

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July, 2005