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**Bibliography**

Note: the contents of this textbook, with the exception of some of the historical and philosophical discussion, derives from the author’s general knowledge of the field of astrophysics. Some of the historical and philosophical material is from the following sources:

*Physics for Poets*, 3rd ed., Robert H. March (New York: McGraw-Hill) (1992)

*The Coming of Age of the Milky Way*, Perennial ed., Timothy Ferris (New York: Harpers-Collins) (2003)

*The Structure of Scientific Revolutions*, 2nd ed., Thomas Kuhn (Chicago: U. of Chicago Press) (1970)

*The Mind of God*, Paul Davies (New York: McGraw-Hill) (1992)

*What Is Real? The Unfinished Quest for the Meaning of Quantum Physics*, Adam Becker (New York: Basic Books) (2018)

*An Introduction to Modern Astrophysics*, 2nd ed., Bradley W. Carroll & Dale A. Ostlie (San Francisco: Perason/Addison-Wesley) (2007)

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