PHENOMENAL PHYSICS

Clifford E. Swartz

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To Barb, who is truly phenomenal

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PREFACE

Phenomenal physics? What can be so unusual or amazing about physics? Of course, physicists think physics is exciting, but that's because it's their life's work. There can be an enormous thrill in discovering a new subatomic particle, or in finding a new way to explain a familiar process. There can also be small but satisfying thrills in observing and understanding the daily natural events around us. Rainbows and hi-fi sets and spinning wheels and soap bubbles are more fun to deal with if you know their scientific origins. The success of physics in explaining everyday phenomena is truly phenomenal.

However, that's not why I named the book *Phenomenal Physics*. Phenomenal also means concerned with phenomena—phenomenological. In presenting the standard topics of physics, I first describe examples from the real world. Each chapter opens with a section called "Handling the Phenomena." You can usually do these activities at home or in a dorm with commonly available materials and in just a few moments. Of course, you can, if you wish, bypass these sections or just read about the activities. That would be a pity. Most people understand abstract ideas better if they first handle the phenomena involved. These activities are not a substitute for laboratory work. Instead, they supplement the demonstrations that many instructors present. You can learn more, however, if you play with these phenomena yourself.

This book contains far more information than you can cover in a one-year course. Different instructors, in different schools, in different years, choose to emphasize particular topics and skip others, but a solid core remains. I have tried to cover the core topics thoroughly, and in the standard sequence. The first ten chapters have few optional sections, matching the traditional treatment of this material in most colleges. From Chapter 11 on, however, there are many topics marked "Optional." Some of these involve treatment that is more sophisticated or requires more complicated math than the basic presentation. Other optional topics, such as the one on the physics of music, are not complicated, but might not be required in your particular course. You might enjoy such a section even if it is not required, or, in future years, you may find it useful for reference.

No calculus is used in the core topics, although some derivations in optional material require simple differentiation or integration. Nevertheless, the text appeals occasionally to geometrical arguments concerning the slopes of graph curves or the areas under them. I did not omit any topic in the standard introductory course because of the calculus restriction. Only simple algebra and a few trig-geometry facts are needed for the core topics. The text uses the international system of units (S.I. units) almost exclusively. Where translation to older units is needed, it is provided. There is a guide to S.I. units in the Appendix as well as a summary of the few math facts needed.

If you glance hastily at the table of contents, you might think that the book shortchanges the treatment of "modern" physics. There are no separate chapters on atomic, molecular, nuclear, particle, or astrophysics. Instead, from Chapter 1 on, the discussions use atomic models and examples that involve astronomical data. I point out many cases where the frontiers of research are only one short step beyond the introductory topic. For example, the nature of mass is a current (and recurrent) problem in cosmology, and I exploit this exciting situation in presenting Newton's laws. The final chapter serves both as a survey of atomic and subatomic physics and as a review of many topics studied earlier in the book. The same situation prevails with regard to biological and physiological applications. The human body and its parts are frequently used for examples in mechanics, fluids, sound, optics, and electricity.

The text contains many border diagrams and pictures. Arthlyn Ferguson skillfully and patiently drew the diagrams in a style meant to resemble the sketches that a professor might put on a blackboard while lecturing. These informal drawings describe, summarize, or sometimes comment on the discussions.

Every few pages the text interrupts itself with a question, often of the "yes, but" variety. Usually these follow some derivation or development where the conclusion should be challenged, or where there appears to be a paradox. Ideally, the reader should pause and try to answer such a question, or at least mull it over for a while. My suggested answer or comment about each question is at the end of the chapter. Students tell me that they have found this type of question useful in other books that I have written. If nothing else, the interruption caused by turning to the end of the chapter serves to waken the reader.

There are several features of the book designed to make your study easier and faster. Each chapter has both an Introduction and a Summary. Before studying a new chapter, read both. Then glance through the section headings. You'll get an idea of where you're heading and what to look for.

You can solve most of the homework problems without using a calculator. In fact, you should always work out the approximate size, or the order-of-magnitude, of an unknown quantity before plugging the detailed numbers into the calculator. Zero in on the answer! For order-of-magnitude calculations, $\pi \approx 3$, $\pi^2 \approx 10$, $1047 \approx 938 \approx 1 \times 10^3$, and so on. In the Appendix, there is a list of handy approximations.

Many people helped to produce this book. Naida Dewey faithfully typed and retyped the manuscript. At Wiley, Don Deneck as the College Physics Editor persuaded me to start the book. His successor, Robert McConnin, shepherded it through the final stages. Rosemary Wellner and Joan Knizeski prepared the manuscript for composition. Ann Renzi was the

designer of the book, and Kathy Bendo was in charge of photo research. The production supervisor was Nina R. West.

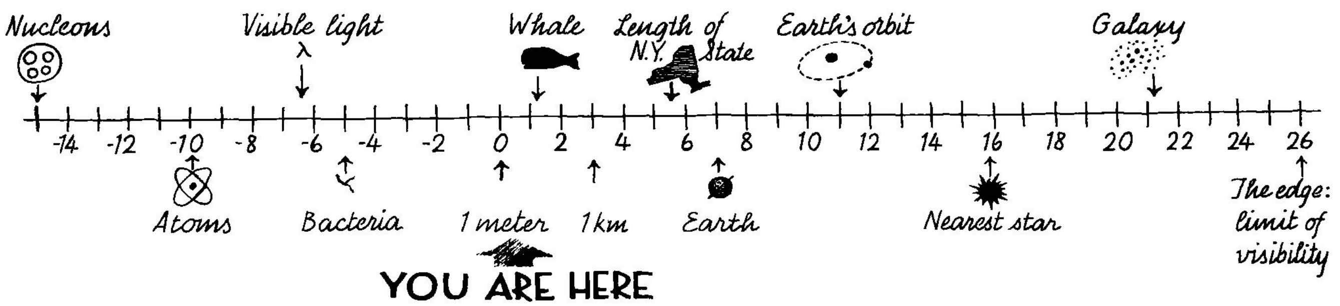
Several physicists read the first draft: Professor Alfred Romer of St. Lawrence University, Professor Arnold Strassenburg of the State University of New York at Stony Brook, and Professor Robert Bauman of the University of Alabama at Birmingham. They brought numerous errors to my attention and made useful suggestions for improvement that I tried to follow. Then Professor Bauman heroically reread a second draft and provided me with detailed criticism that was crucially important. No doubt some errors may remain. Blame me, or better yet, let me know and I will try to correct the error. Ater thirty years of teaching physics, I still find lots of things that I didn't know I didn't know before.

I hope that most of you who read this book are doing it because you want to learn more about our world. Some, I know, are taking physics only to fulfill some requirement. In either case, I hope you end up enjoying the book and the course work. We live in a mysterious and phenomenal universe, and, as far as we know, we're the only ones around who can comprehend it.

Clifford E. Swartz

CONTENTS

THE SETTING AND THE DRAMA 1



In fact, that's where we all are. The chart covers the size of everything that exists, from the smallest subatomic distance that has been measured, to the very edge of the universe. We stake out this entire realm as the subject of our study. Humans, living in the middle range of sizes, have discovered regularities and laws that link the behavior of atoms and the nature of galaxies. In probing both the microworld and the macroworld, we also learn more about ourselves.

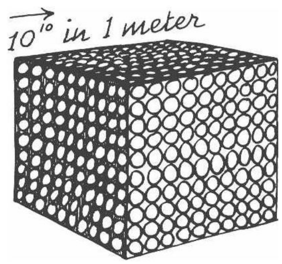
SIZES AND DISTANCES

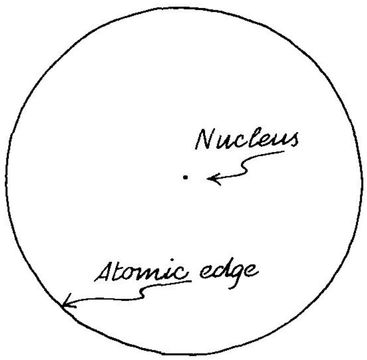
In order to map the whole universe and put it on a single page, we had to use a power-of-10 scale. As you go from left to right, each unit is ten times larger than the one before it. The basic unit of length in this map is the meter (m), a little longer than the English yard. The meter is shown at point 0 on the scale, since 10^0 is equal to 1. Another way to think of the scale markings is to visualize them as being on a logarithmic scale. "One meter" is at the 0 point, since log 1 is equal to 0. Take a look at some of the other familiar points on the map. A kilometer (about $\frac{5}{8}$ miles) is noted at point 3. A kilometer (km) is 1000 meters; the log of 1000 is 3, and 10^3 is 1000. Similarly, a millimeter is at the point -3 since 10^{-3} equals $(\frac{1}{10})^3$.

Question 1-1

We interrupt the text from time to time to challenge or emphasize what has just been said. The questions we raise will not always have definite answers. You can find our answer or opinion at the end of each chapter, but you should wrestle with each question for a while before turning to our solution.

The question at this point concerns the location of humans on the map of the universe. They are placed very close to zero. Does that make them only a little taller than 1 meter?



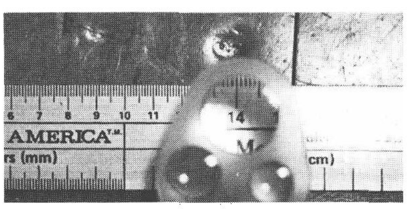


For an actual scale drawing, the atomic diameter would have to be at least 10,000 times the nuclear diameter. If the dot representing the nucleus is 0.1 mm, the atomic sphere should be 1 m in diameter.

Living creatures occupy a very small region of this map. The largest whale is no more than 30 meters long, and so is pictured at a point less than 2 on the map. Biological cells can be seen with microscopes and are larger than a millionth of a meter, shown on the scale at -6. (Since 10^6 is 1 million, 10^{-6} is 1/1,000,000, or 0.000,001, or 1 millionth.)

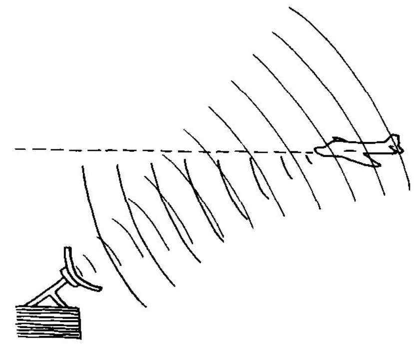
Marching down the scale into the microworld, we find atoms at -10. Most atoms are about the same size. From hydrogen to uranium, few of them differ by more than a factor of two in diameter. Note that if each atom is 10^{-10} meters across, you could line up 10^{10} of them, shoulder to shoulder, in a distance of 1 meter. Since 10^9, a thousand million, is one billion, that would be 10 billion atoms. The atom itself is huge compared to its tiny nucleus. Depending on the element, the nuclear diameter is smaller than the atomic diameter by a factor of 10,000 to 100,000. That would put the nucleus between -14 and -15 on the universe map. It is possible to measure quite accurately the diameters of the protons and neutrons that make up the atomic nucleus. As we will see in a later chapter, sizes much smaller than this are not meaningful in current research. We put the lower limit of our universe at 10^{-15} meters.

Does it make sense to talk about sizes this small? Only if we can measure them in some way. With your unaided eyes, using visible light, you can see the shapes of objects that are one millimeter (1 mm) across. A magnifying glass can provide a magnification of up to about 10, and a child's microscope may have a magnification of 100. Even the best research microscopes do not have magnification greater than 1000 to 2000. Since your unaided eye can see an object that has a size of 1 mm, with a research microscope it can see objects that are $\frac{1}{1000}$ of 1 mm, or 10^{-6} meters, which is called a micrometer. (The older name is micron.) The limit of magnification is caused by the fact that light has a wavelength, or a size, of its own. You cannot "see" something if the probe is larger than the detail you are trying to see. Electron microscopes use electrons as probes. These can be smaller than the wavelengths of visible light. Magnification by a factor of over 10^5 has been achieved, making it possible to see objects that are only 10^{-8} meters across.

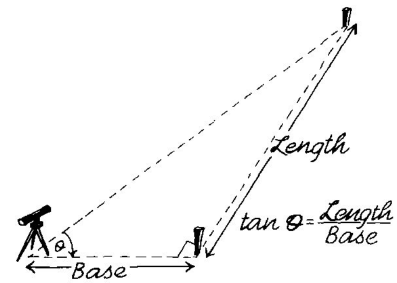


For sizes below the electron microscope range, we have to scatter electrons or other subatomic particles and analyze their scattering patterns. We'll examine these methods in later chapters. Note, however, that in seeing anything, we shoot or probe with something, and then detect what happens to the probe. As you look at this book, for instance, light is being scattered from the print and the page. A small fraction of the reflected light enters your eye, where the information is processed, sent on to the brain, and recognized. In much the same way, an airplane can be seen by scattering radar waves from it, and detecting the waves that are reflected to the receiver. You could not read this book by scattering radar waves off it, however. The radar waves are about the size of the book itself, and so are too broad a probe to detect the printed details.

If it only makes sense to talk about sizes that we can measure, how can we justify using some of those distances on the right side of the universe map? You can measure a whale, or even a country, by fairly straightforward methods. Surveying is still done by measuring baselines and angles. The length of the meter was originally calibrated in a complicated and rather misguided surveying project. At the time of the French revolution in 1791, the French National Assembly voted to make the unit of length equal to 1/10,000,000 of a quadrant of the earth's surface. The only reason for prescribing such an exact ratio for an arbitrary standard was so that the standard could always be reproduced—presumably the earth would never change. A surveying party actually measured the earth's arc all the way from Dunkerque on the English channel to Mont-Juoy near Barcelona, Spain.



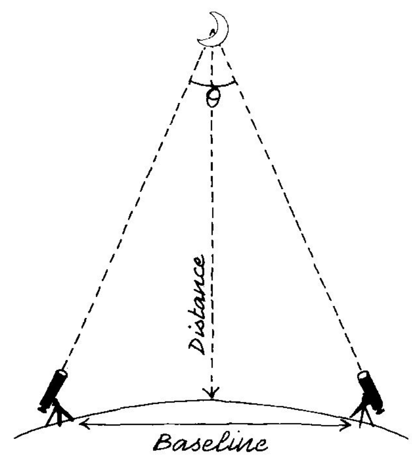
A radar scanner sees an airplane. The probes are electromagnetic waves much longer than those of visible light.



Question 1-2

What good did that measurement do them? Even if you know the length of France, how can you tell what fraction that is of the earth's circumference?

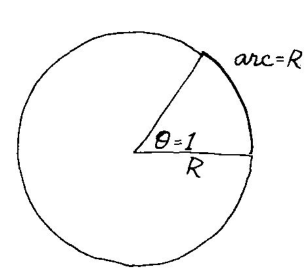
The trouble with using surveying techniques is that you need a measured baseline. To measure the distance to the moon, the largest baseline available is the diameter of the earth itself. Actually, a much smaller distance must be used since there are problems if telescopes are sighted too close to the horizon. Suppose you use two observatories 1000 km apart (about 630 miles). Both telescopes have to aim at the same point on the moon, and *at the same time*. (The moon is a moving object.) The geometry of the situation is shown in the diagram. By measuring the angle between the vertical and the moon at each location, the subtended angle can be found. That angle is approximately equal to the distance between the two telescopes divided by the distance to the moon.



$$\theta = (\text{baseline})/(\text{distance}) = 1000\ \text{km}/384{,}000\ \text{km} = 1/384\ \text{radians}$$

$$= \frac{1}{384}\ \text{radians}\left(\frac{57^\circ}{\text{radian}}\right) = 0.15\ \text{degree of arc}$$

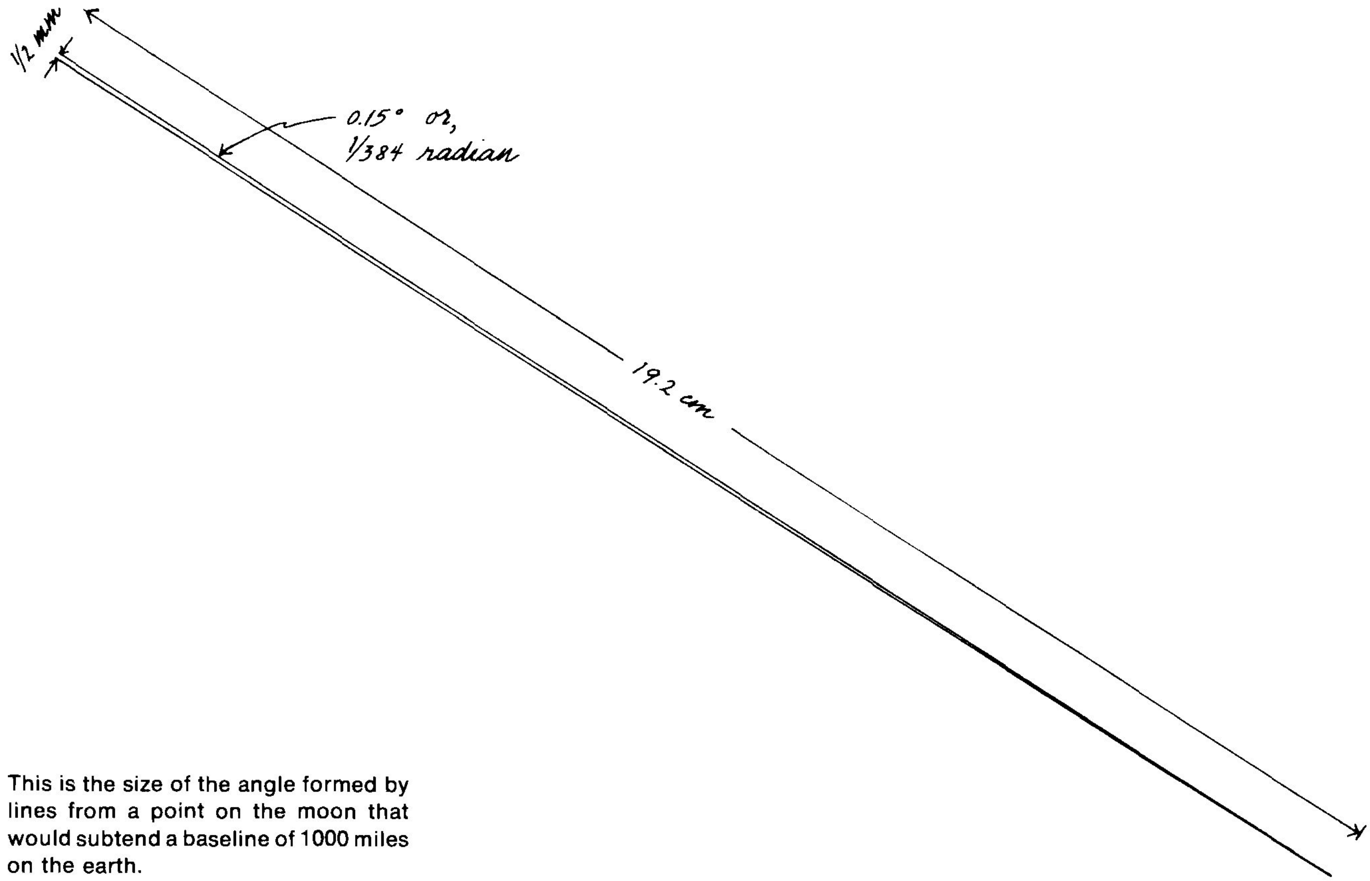
An angle of only 0.15 degree is small, but easy enough for one telescope to measure. It's a little more difficult to determine that small an angle by having two telescopes synchronize their observations and subtract individual measurement.



θ = arc length/radius When arc length equals R, θ equals 1 radian. There must be 2π radians in a circle or in 360°. Therefore, 1 radian ≃ 57°.

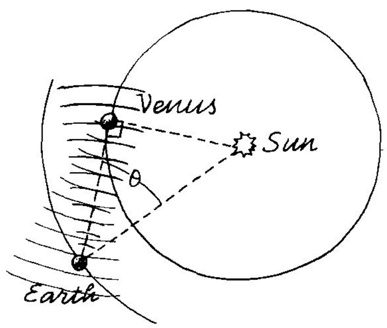
Question 1-3

Isn't it necessary to use trigonometry to solve this problem? The distance between moon and earth is the long leg of a right triangle.



This is the size of the angle formed by lines from a point on the moon that would subtend a baseline of 1000 miles on the earth.

Half the baseline is the short leg. Therefore, the tangent of one half the subtended angle is equal to the ratio of one half the baseline divided by the moon-earth distance. Isn't this method right and the other wrong?



Earth-Sun distance can be measured by measuring Earth-Venus distance with radar, and knowing the angular relationships at that time of the Earth-Venus-Sun triangle.

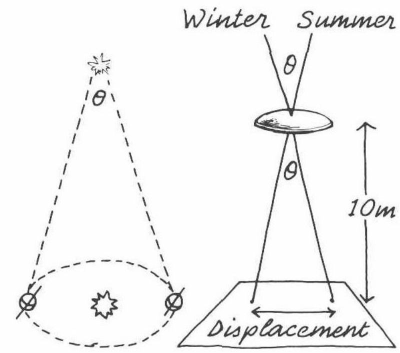
The distance to the sun is 1.5×10^{11} m. If a baseline on the earth of 1000 km (1×10^6 m) were used, the subtended angle would be only 6×10^{-6} radians, or about one second of arc. That's too small an angle to measure for a wide target like the sun. The earth-solar distance is actually measured by a comparison of other solar system distances and angles. The earth-moon and earth-Venus distances are measured these days by timing the flight of radar pulses from earth to object and back again. Since the velocity of light—which is the same as that of radar—is known very precisely, the distance measurement can be as precise as the measurement of time between sending the pulse and receiving the echo.

The distance to the near stars is also determined by surveying techniques. In this case the baseline is unearthly! It is the diameter of the earth's orbit around the sun. Even though that baseline is 3×10^{11} m long, the distance to the nearest star makes the angular measurement tricky.

Question 1-4

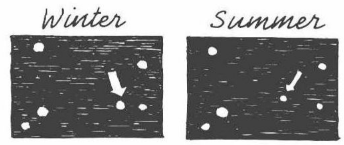
If the distance to the nearest star is 3.8×10^{16} m, what angle is subtended by the baseline?

To make measurements using the orbit baseline, the same telescope photographs a star field at six-month intervals. When the two photographs are superimposed, most of the star images lie exactly on top of each other. However, the fall and spring images of a very near star will be slightly displaced from each other. The ratio of that slight displacement to the focal length of the telescope is the same angle as the ratio of baseline to stellar distance. For one second of arc and a focal length of 10 m, the image displacement on the photographic plate is found as follows:

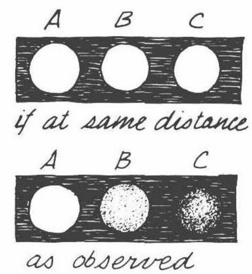


$$\theta = 1 \text{ sec} \approx 5 \times 10^{-6} \text{ rad} = (\text{displacement})/(10 \text{ m})$$

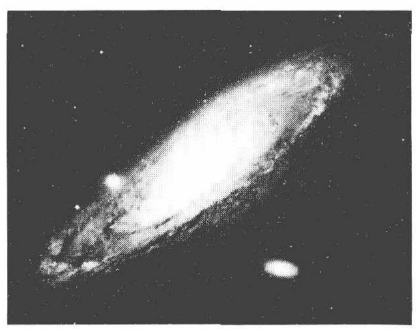
The image displacement is about 50×10^{-6} m, or 50 micrometers. The distance to the stars must be measured with a microscope!

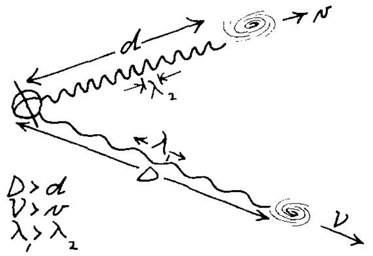


The nearest star to our sun is about four light-years away. A light-year is a unit of distance, not time. It's the distance that light travels in one year and is equal to 9.56×10^{15} m. (In the same way, we might say that the moon is 1.3 light-*seconds* from the earth.) Triangulation, or surveying techniques, can be used to measure distances as great as one hundred light-years or so. However, this is hardly a step out into our galaxy, which has a diameter of 100,000 light-years. To measure those distances, we must appeal to conclusions that follow from a whole set of observations about certain types of stars whose brightness varies in a periodic fashion. The argument goes like this: if you know how bright a star really is, you can tell how far away it is by measuring the brightness you see here on earth. For instance, suppose that all stars were really the same brightness but that we observe star A to be four times brighter than star B and nine times brighter than star C. Then B would be twice as far away as A, and C would be three times as far. The intensity of light from a point source falls off as the *square* of the distance. If you can measure the distance to A by triangulation, you can calculate the distances to B and C. Of course, stars are *not* all the same size and brightness. There are relationships, however, between the intrinsic brightness of certain stars and such characteristics as their color and frequency of changing brightness.

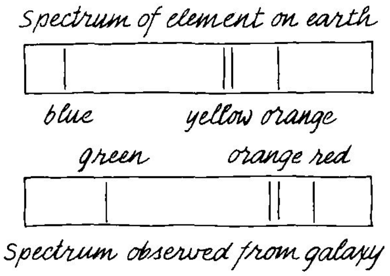


Relative brightness methods are also used to measure distances to the near galaxies. These galaxies are island universes, each containing millions or billions of stars. Our own galaxy contains about ten billion (10^{10}) stars, and looks something like our near neighbor, the galaxy that can just be seen with the naked eye in the Andromeda constellation. That galaxy, as you can see in the illustration, has a pinwheel shape—just like our own galaxy. Galaxies exist in a variety of forms, including spherical. Our solar system is about two-thirds of the way out on one of the arms of our galaxy. When we look toward the hub we see a high concentration of stars that appear in





The galaxy at distance *D* is much farther from the earth than the galaxy at distance *d*. Because the universe is expanding, the velocity away from us of the far galaxy is greater. Therefore, the light of a particular element in that galaxy has a longer wavelength.

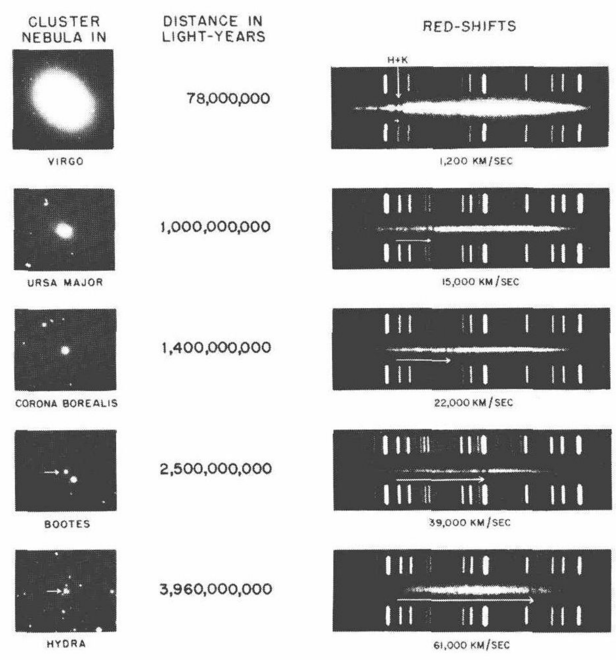


If a galaxy is traveling away from us, the pattern of its spectral lines shifts toward the red.

the night sky as the Milky Way. From detailed counts of small samples of the sky, we know that there are about ten billion (10^{10}) galaxies in the universe.

There is another method of measuring distances to the far galaxies. The velocity of a galaxy with respect to us can be measured by its Doppler shift. If a source of waves is moving toward an observer, the frequency of the waves seems higher. A train whistle, for instance, has a higher pitch as the train approaches a listener. As the train passes and races away, the pitch abruptly lowers. In the same way the characteristic patterns of light produced by various elements in distant galaxies are seen on earth to be shifted to lower frequencies. The amount of this "red shift" to long wavelengths tells us how fast the galaxy is fleeing from us. It turns out that all the galaxies are flying apart from each other. The universe is expanding. Furthermore, the further away the galaxy, the faster its speed away from us. Since this rule is followed by the close galaxies whose distances we can measure by brightness methods, we use the rule to find distances of the far galaxies by measuring their red shift velocities. In this way galaxies have been observed that are ten billion light-years away from us. They are traveling at speeds over half that of light, and are close to the edge of our visible universe.

If, as seems likely, the universe started in an immense explosion about fifteen billion years ago, and has been expanding ever since, there is, indeed, a limit to the universe. Many of the details of the origin and of the far reaches of the universe are still shrouded in mystery. Regardless of the details, however, there is a limit to *our* universe at about 10^{26} meters. Beyond that distance, any object would be traveling away from us so fast that any information sent to us (such as the characteristic patterns of the light produced by different elements) would be red-shifted into the background noise of low energy radiation. Blue light, for instance, would not just shift to red light, but might have the much longer wavelength of radio waves.



Note the horizontal white arrow drawn on each spectrum, showing the position of one prominent spectral line, appearing here just as a dot. The lines above and below the galaxy's spectrum show an earth spectrum.

Question 1-5

How long would it take something traveling at the speed of light (3×10^8 m/sec) to go 1×10^{26} meters?

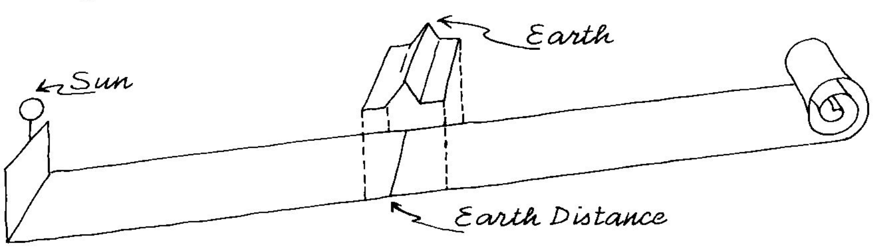
HANDLING THE PHENOMENA—DISTANCES

Physics is not math or logic. All our theories and models are useful only if they predict real events in the real world. Futhermore, understanding physics is not just an intellectual exercise. The phenomena must be handled. When you talk about velocity, you should have some familiarity with various velocities either by experiencing them or by measuring them. When you talk about forces, you should feel them in your muscles. Such a goal is limited, of course. In our study we want to go far beyond the normal human experience, both to the very large and the very small. Nevertheless, there are benchmarks along the way that can be experienced and comprehended.

In every chapter we propose ways to handle some of the phenomena described in that chapter. Sometimes this will be done through the use of models or analogies. These are not laboratory exercises, but are simple things to do using materials available at home or in the dormitory. The precision required and the time to be spent are usually very small.

How on earth can you experience the beginning topic of this chapter? Perhaps you could build your own universe! Better yet, why not construct a scale map of something close to home, such as the solar system? The map of the universe that we presented was built on a logarithmic scale. To better understand the nature of that scale, build your solar system on a *linear* scale. That's the kind used in ordinary road maps. A state map, for instance, might use a scale of 20 miles to the inch (or 10 km to the cm). We list below the distances of the planets from the sun, and also the diameters of the planets and sun. Choose a scale so that Pluto can be included in whatever room or hall you use, but also a scale so that the sun is more than a point. Note the problem of trying to use a scale that represents the size of each planet and also fits the whole system into a reasonable indoor space. If the scale is such that the earth diameter is 1 cm, the earth-sun distance will be over 100 m. One suggestion, which still requires a corridor or good-sized room, is to use a scale of 1 cm to 5,000,000 km. The model of the sun itself will then be small, but more than a point. The other planets will be just points, but their locations can be marked with arrows on paper tabs. If you want a solar system that you can roll up and put in your pocket, make the scale model on a long paper tape, such as a cashier's tape. The diagram shows how to make a marker tab that will fold down when rolled.

Why go to the trouble of making such a map? Perhaps you will see something about the nature of the solar system that is not apparent from the



Planet	Average Distance from Sun (in 10^6 km)	Mean Diameter (in km)
Mercury	57.9	4840
Venus	108.1	12520
Earth	149.5	12740
Mars	225.8	6780
Jupiter	777.8	139800
Saturn	1426	115000
Uranus	2868	47400
Neptune	4494	43000
Pluto	5908	5800
Sun	——	1393000