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# Measure Solar System Objects and Their Movements for Yourself!

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Springer

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# Preface

Until two-and-a-half years ago I had done no astronomy for 30 years. I had messed about with a home-made telescope as a kid, and taken an astrophysics class which barely mentioned the Solar System as part of my physics major, but that was it.

This course inspired me enough that I thought about studying astrophysics in graduate school, but I chickened out, figuring I would never get a job. So I did a PhD in semiconductor theory instead, only to find that there were no jobs in that either; so I washed up in medical device development, and pretty well forgot about astronomy.

In January 2006, my wife offered to buy me a 6-in. reflecting telescope. I knew so little about it that for almost a year I had the equatorial mount pointing south instead of toward Polaris. The "local" astronomy club met 70 miles away, so I rarely went, and in desperation I founded one locally. At last I had some friends to teach me the basics.

Gradually I noticed that although these folk knew much more about constellations, telescopes, and photography than me, I did look at the planets in a different way from them. I got little flashes of insight such as noticing that if Venus is at half phase, the angle between us, it, and the Sun must be a right angle, so the Sun, the Earth, and the Venus at that time made a right angle triangle, from which you can work out the distance to Venus. I do not think they were quite sure what to make of me and my mad ideas. One or two were unreceptive, but most club members seemed interested. I began to realize that I had a slightly different story to tell. This book is it.

You do not need a PhD in physics or astronomy to understand the Solar System. You can work out the basic layout of the Solar System from your backyard, even if you live in a brightly lit town like me.

At one level, this book is my collection of astronomy "war stories." I make no bones about having learnt a few lessons the hard way, and having discovered occasionally that I had been doing silly things. It is also the story of a journey from beginner to halfway competent astronomer. I have written the book like this to emphasize that you do not need to be any kind of expert to carry out the projects I suggest here.

A key message I want to get across is that I had no master plan to map out the Solar System. I quite deliberately leapt in where angels feared to tread, and sometimes took photos to see if I could detect any planetary or satellite movement at all. For example I knew from my early observations that Saturn does not move much. I was not at all sure I would see any movement, but I did. My activities gradually evolved from messing about toward more systematic study. To some extent I began to think that I had seen Jupiter often enough; and was looking for new things to do.

My journey through the Solar System is also incomplete. From England, Jupiter is practically on the horizon this year; and I have barely scratched the surface of what I could learn about it. So Jupiter will have to wait. Because the local light pollution is too great, I could not find Uranus nor Neptune reliably. Next autumn, I should be able to look for the larger asteroids.

There is another thing: my equipment is nothing special. I have a beat-up second hand 8-in. Newtonian reflector on a dual-axis driven EQ5 mount, as well as the 6-in. telescope my wife gave me. I have two Philips SPC900NC webcams, and a laptop PC. All the software I used is available for free, or an equivalent is, except K3CCD Tools™, which cost me US $50, and the software driver for my webcams, which of course came with them. Your equipment does not need to be fancy either.

To follow this book, you will undoubtedly need to know some high school geometry. Ideally you have done freshman year math in North America as part of a science or engineering course; or A-level maths or the Scottish or Irish equivalent in Europe. (I gave up on whether to write "math" or "maths" and will stick to mathematics.) If you picked up some basic calculus and geometry at night school on an apprenticeship of some kind, that should suffice. I have deliberately avoided using mathematical methods that require professional level skills: my methods are quite deliberately rather basic and downhome. This book is emphatically not for professional astronomers. Although I started out intending to write a book requiring basic calculus, I ended up using much less of it than I expected to. At a pinch you could skip those parts where I do use it.

I have, however, assumed that your mathematics are very rusty. Mathematical skills are not like swimming. You can do no swimming for years, and yet get straight in the water and swim again. A better analogy to mathematics is like letting your arm go numb if you lie in an awkward position. As the arm comes back to life, you will get pins and needles, which are no fun at all, but once they go away you will be fine. I think mathematics is a bit like that. At the start of the book, you may find the calculations uncomfortable, but once you find your stride they will get easier. Please allow a little time for this to happen; and do not worry. Almost every other reader will experience the same. Do not expect to read the book all in one go like an airport paperback. Take your time, think about it, take lots of breaks, and be prepared to have a pencil and paper handy to work through the calculations. Real calculations do not come in neatly packaged, same-size chunks like school textbook problems. They may only use textbook concepts, but some can be lengthier than simple textbook examples.

I have added Appendices A and B to help you get started. These are not primers: they are necessarily minimalist, and are there because most of you will not live in a house with a dozen mathematics texts. I am supposed to be writing a book about astronomy here, not mathematics. What I have tried to do is to provide all the algebraic manipulation. Most people (me included) hate seeing calculation steps missed out, or worse yet left as an exercise for the reader. It is like having to navigate in the pre-GPS era with one missing road sign at a busy intersection. You are stymied.

I am a great believer in the evidence-based approach. That is a key part of the ethos of this book. You can look up the distances of the planets from the Sun on the Internet in 10 min. But how do you know that these distances are close to right? What I want to show you is how you can check the approximate truth of the planetary distances that every astronomer "knows." I find it much more satisfying to know where a fact comes from. In the first instance, the thing is to get a rough idea. That is what I aim to give you. It is good science to get a rough idea before you look for a detailed one. If you want to send a rocket to Mars though, you will need more sophisticated methods than I offer.

Where did I get my methods from? I looked in many books, notably those by French; Danby; Murray and Dermot; Ferguson and Tatum[1] listed in the bibliography. Some I knew from my college days, notably my freshman mechanics course. I concluded that the methods given in the celestial mechanics texts would be beyond most amateurs, because they focus on elliptical rather than circular orbits. The only one who treats circular orbits is Tatum, who points out that for most planets the orbits are almost circular. Even his treatment is not suitable for our purposes. First, he leaves most of the analysis as an exercise for the reader (see above). Second, his method for obtaining planetary distances requires knowing things you have no hope of measuring. I do not think he has tried his method in anger, or he too would have found this out. I only noticed because I did try his method. So in the end, I made the methods up. I do not believe for one second that I am the first person to analyze circular orbits. I am sure many others have, but I could not find where they wrote up their analyses. I was proud of my cleverness in one or two places, but mostly I think I was just doing my job as a physicist.

I have seen "Monte Carlo" statistical methods used for many things, e.g., in Wall and Jenkins' *Practical Statistics for Astronomers* or the *find_orb* orbit determining software (http://www.projectpluto.com). I did not copy my method for performing least squares analysis from anywhere. It is a technique a professional physicist like me ought to be able to apply, just like a dentist should know how to drill teeth. I think Monte Carlo methods are accepted to be a last resource of the mathematically

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[1] Tatum, J.B. (2007) Celestial Mechanics, online book found at http://www.astro.unic.ca/~tatum

desperate, a state in which I most certainly was. In the sense that they require a lot of number crunching, they are not very efficient; but for our purposes their inefficiency is of little consequence. Your PC should handle these methods easily. They may take up to an hour each per planet on a 10-year-old computer, and much less on a newer one, but what is the big deal about that? You can spend a lot more time than that sitting by your telescope waiting for clouds to clear. The key advantage of Monte Carlo methods is that they are simple and easy to understand.

I firmly believe that if you do not understand a statistical method, you should not be using it. For example, in business school, we were taught a technique for hypothesis testing (the chi-square method) without being told how it works. That is outrageous: to proclaim the truth or otherwise of a hypothesis without knowing why is no better than to assert that retrograde planetary motion causes bad karma. I have provided an appendix deriving the statistical methods I use from first principles. You will definitely need calculus to follow it. If that is beyond you, you will survive by skipping this appendix. However, you will have to accept that random scatter in measurements tends to be distributed in a “bell curve” with most measurements near the average. You will also have to take my word for it that when fitting lines to data, this implies that you should use the method of least squares. Your high school geometry and algebra will enable you to implement this method even if you do not understand where it comes from.

Since I work in new product development, I am now also a qualified engineer, and have freely borrowed ideas from that world. In particular, I have never seen or heard of anyone using Computer-Aided Drafting (CAD) software to make measurements from astronomical photographs. You can download CAD software for free. This software usually allows you to import digital images, and has dimensioning tools to allow lengths and angles to be very quickly and accurately added to engineering drawings. What I did was to use the software to draft circles, and occasionally ellipses, freehand around the celestial objects, and use the dimensioning tools to make the measurements. There is professional astronomical software around with not dissimilar capabilities, but it only runs on computers with Unix or Linux operating systems. There is a package called Astro Art (http://www.msb-astroart.com) which does it all for you, but as far as I can make out it is a “black box” that does not tell you what it did. By now you should be able to guess whether I approve of that.

If you enjoy this book I will have been successful, though I would not of course know it. The thing is to have a go. Although my recipes have all been tested, and I report how good they are, you need not follow them precisely if you do not want to. I primarily want to feed you a few ideas.

If someone is inspired to contact me at john.clark@finerandd.com with ideas about observing the Solar System, or even write a book, showing how they learned lots of fun stuff about Solar System objects, I would be delighted.

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# Acknowledgments

I am long enough in the tooth to owe intellectual debts to many people. It starts with my parents, of course. The inspiring teaching of my school physics teacher, the late Brian Salthouse, helped shape my decision to study science – I could just as easily have become a linguist or a classicist. A few of my undergraduate teachers were terrible, and should have been fired, but those who were good were very, very good. In an astronomical context I would single out Gary Gledhill, who taught my freshman mechanics course. To this day I regard it as one of the great intellectual experiences of my life. I have used quite a bit of the material from that course here. I would also like to thank Peter Williams, who taught me Astrophysics and was my personal tutor throughout my bachelor's degree; and one person who I think would be surprised: Wladimir von Schlippe. He set me up for life with an undergraduate mathematics course. At the time I was critical with the certainty of youth, because he was not flashy and sparkling. But so what? His teaching was clear and thorough, and I learnt as much mathematics from him as from anyone. I still feel ashamed that I was so critical of him.

Over the years, I owe debts to other people from whom I learnt a lot about science: the late Paul Butcher, my PhD supervisor; Phil Taylor, my first boss; Bill Potter, my next one, who hired me a second time 12 years later; another boss Mark Wickham, who also hired me twice in two different firms; and three friends who over the years have challenged me with tough questions: Charles Jenkins, Nick White, and Jim Franklin.

I must also thank the people who read and criticized the manuscript, primarily my wife and daughter, but also Paul Millar and Gary Wassell. Paying my daughter £5 ($10) for every mistake she found proved to be expensive. My Dad provided the hand drawings. Nevertheless only one person is responsible for any remaining errors: me.

Of course the debt I owe my wife, daughter, and parents for love and support is beyond my capacity for repayment.

I have learnt a lot of observational tricks from various astronomy club members, including Sue Napper from Norwich Astronomy Society; and Freddy Rice, Adrian King, Trevor Nurse, and Darren Sprunt from West Norfolk Astronomy Society.

Now I have had to learn a new art: how to put a book together. The staff at Springer, John Watson, Maury Solomon, and Turpana Molina, have guided me patiently through this process.

# Contents

# About the Author

John Clark's wife bought him a telescope in 2006. He was immediately and badly bitten by the astronomy bug and started taking photographs a year later. Feeling rather isolated, he founded the West Norfolk Astronomy Society, and was recently awarded a grant by the Institute of Physics for astronomy outreach activities. An engineering physicist by profession, he brings insights from both engineering and physics into his astronomy in a unique combination. He lives in King's Lynn, England, with his wife and daughter; and with his parents nearby.

CHAPTER ONE

# How Do We Know That Venus Orbits The Sun?

Venus exhibits phases like the Moon. It is a lot further away, so it looks a lot smaller than the Moon. The phases are not visible to the naked eye, except to a very few sharp-eyed people; and were unknown until the advent of the telescope about 400 years ago.

You cannot see the phases very well in 10 × 50 binoculars, but my 6 in. *f*/5 Newtonian telescope shows them very nicely. At least it did in late winter 2006. The crescent phase was unmistakable. But when it first appeared in the evening sky around January 2007, I was very puzzled because I had seen the phases so easily the previous winter just before sunrise. I could not see any phases. The darn thing was just a bright blob even at maximum magnification.

I told my wife, not very confidently, that it must be much further away than a year ago. Was I right?

It was about this time that I first tried my hand at photography with a webcam. My first photos were not a pretty sight. It took me a couple of months to get around to photographing Venus (Fig. 1.1). By this time I had bought an 8 in. *f*/6 telescope through e-Bay, which was a big improvement on the 6 in., mainly because it has an electric focuser and an EQ5 mount, which is much stiffer than the EQ2 on the 6 in. model. The better optics and the dual axis drive certainly do not hurt, but to me they are secondary benefits for photography. Anyway, it was April 10th by the time I first had a go at photographing Venus. I could now resolve its shape. It was gibbous.

I cannot claim to have been very systematic about my photography. The weather was not helpful. Nor, at this point, was my rather variable photographic technique. Nevertheless I watched it grow bigger, and watched the phase wane. By late May it had reached half-phase.

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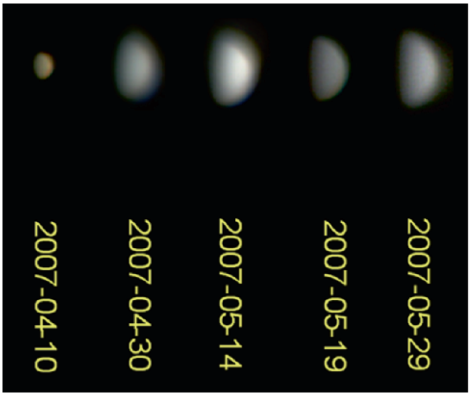


**Fig. 1.1.** The author's own photographs of the phases of Venus, taken with the same telescope at the same magnification, over a 7-week period.

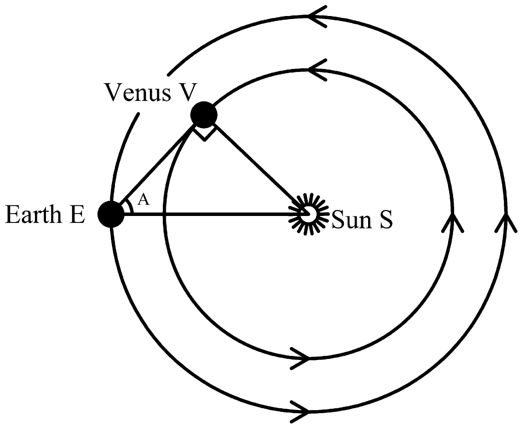


**Fig. 1.2.** If Venus is at half-phase, the Earth-to-Venus line must be at right angles to the Sun-to-Venus line. Together with the Sun-to-Earth line, these lines form a right-angle triangle. We shall call the vertices of this triangle S, E, and V. When the angle SVE is a right angle and Venus' phase is waning, the configuration of the planets is known as the Greatest Eastern Elongation of Venus.

At this point I had a brainwave. If the planet was at half-phase, the angle between the Earth-to-Venus line and the Venus-to-Sun line must be a right angle.

"So what?" you ask.

Well, from Fig. 1.2 we see that the Earth, the Sun, and the Venus make the right-angle triangle SVE, where S, E, and V mean "Sun," "Earth," and "Venus," respectively. The right angle is at V, as shown in Fig. 1.2. The properties of right angle triangles are well documented. I can use them to estimate the distances EV and VS if I know the distance ES. To a first approximation, the distance ES is known as one

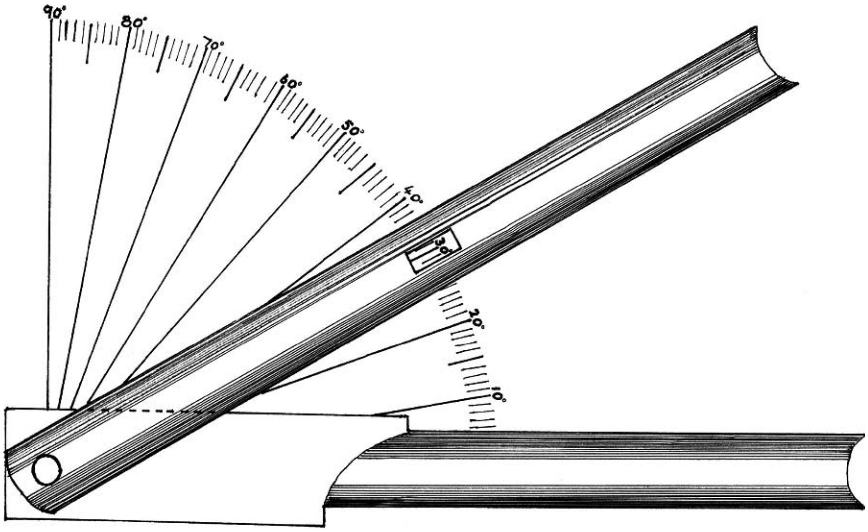


**Fig. 1.3.** My home-made device for measuring the angle between heavenly bodies. It consists of a cardboard backing onto which is fastened an angle scale drawn with computer-aided drafting (CAD) software. Thumb tacks are used to attach two cardboard coat hanger inserts of the type dry cleaners use to hold long pants in place.

astronomical unit (AU). More accurately, 1 AU is an average Earth-Sun distance: the orbit is of course not a perfect circle.

Not quite: I need one more piece of information – I need to know the angle *A* in Fig. 1.2. This means I need to measure it. I tried using rulers and a protractor, but got nowhere. It was time for a bit of second childhood while I made a measuring device.

Figure 1.3 hows the offending item. It consists of a cardboard backing onto which is fastened an angle scale drawn with computer-aided drafting (CAD) software. Thumb tacks are used to attach two cardboard coat hanger inserts of the type dry cleaners use.

The trick was to wait until just before sunset, when the Sun was not blinding, and place my eye where the two cardboard inserts met. I pointed one cardboard insert at the Sun, the other at Venus. The v-shaped nature of the inserts made the pointing a little easier. I managed this twice on the evening of 29 May, and recorded angles of 46° and 47°. Although my device worked, it was not exactly user-friendly – measurement was difficult.

Incidentally, the planetary arrangement shown in Fig. 1.2 is known as the "Greatest Eastern Elongation" of Venus. This is because if the angle *A* were to get any bigger than this, the line EV would miss the orbit of Venus completely. Therefore angle *A* cannot get any bigger than at Greatest Eastern Elongation.

We now do some simple trigonometry. Taking the angle *A* in Fig. 1.2,

$$\sin \mathrm{A} = \frac{\mathrm{SV}}{\mathrm{SE}}. \tag{1.1}$$

But we have measured *A* to be about 46.5°. So (1.1) becomes

$$\begin{gathered} \sin A = \sin 46.5 = \frac{\mathrm{SV}}{\mathrm{SE}} = 0.725; \\ \therefore \mathrm{SV} = 0.725\,\mathrm{SE} \approx 0.73\,\mathrm{AU}. \end{gathered} \tag{1.2}$$

In (1.2), the symbol "≈" means "is approximately equal to." I now have a distance estimate: the distance from the Sun to Venus is between 0.72 and 0.73 AU. Bakich[2] reports values between 0.7184 and 0.7282 AU, with an average of 0.7233. Given the crudity of my measurement, I did better than I deserve. One of the weaknesses of the scientific measurement is that it gets awfully tempting to stop experimenting when you find the answer you were looking for.

Far from falling into this trap, I will show you later how I double-checked my measurement. I waited until Venus was next at half-phase, but waxing instead of waning. This is called the "Greatest Western Elongation" of Venus. If I could predict the time at which this happened, I would have understood the relative orbits of Earth and Venus correctly. In particular, a prediction of the time at which the planet is next at half-phase can be checked with my telescope.

To make this prediction, I need to show you a little bit about how planetary orbits work. Since neither the Earth nor Venus has a very elliptical orbit,[2] I can get away with assuming that these two planets have circular orbits. This assumption simplifies the calculations from graduate-school level to freshman year science or engineering (A-level mathematics or physics in Britain).

## Circular Motion

The physics of circular motion was first solved by Christiaan Huyghens in 1688.[3]

First, I will show you how to work out this physics in a way that uses no calculus.

Imagine a point which goes around a circle of radius *r* with constant speed *v*. Such a point is shown in Fig. 1.4. Just as the radius *r* keeps its magnitude but goes around in a circle, so does the direction of *v*.

I am going to define a unit of angular measure called a "radian." Figure 1.5 shows how the angle is one radian when the length of the arc between two radii is equal to the length *r* of the radius. Since the length of the entire circumference is $2\pi r$, one complete circle contains $2\pi$ radians. In other words, $2\pi$ radians = 360°, or 1 radian ≈ 57.296°.

If in Fig. 1.4 the time taken to complete one revolution is *T*, then the time to complete one radian is $T/2\pi$. We therefore say that the angular velocity of the rotating point is

$$\omega = \frac{2\pi}{T}, \tag{1.3}$$

where the Greek letter $\omega$ (lower case omega) is the traditional symbol for angular velocity in radians per second.

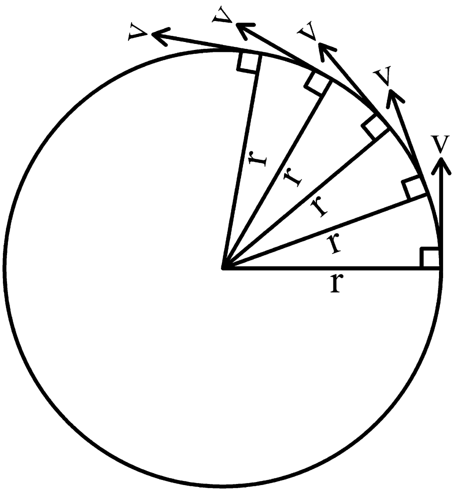


**Fig. 1.4.** A point on the circumference of a circle of radius *r* rotates around it with uniform speed *v*. Since the velocity is always perpendicular to the moving radius, it too goes around in a circle.

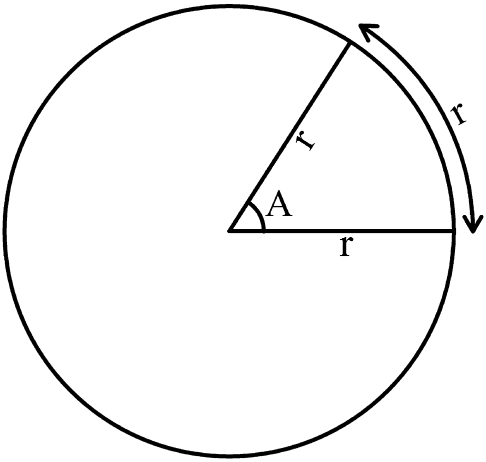


**Fig. 1.5.** If the length of the arc between two radii is equal to the length *r* of the radius, the angle *A* is said to be equal to one radian. Since the length of the entire circumference is $2\pi r$, one complete circle contains $2\pi$ radians. In other words, $2\pi$ radians = 360°.

What is the value of $T$? Speed is the distance traveled in unit time.

$$\begin{aligned} \text{Speed} &= \frac{\text{Distance}}{\text{Time}}; \\ \therefore \text{Time} &= \frac{\text{Distance}}{\text{Speed}}; \\ \text{i.e.,} \quad \mathrm{T} &= \frac{2\pi r}{v}. \end{aligned} \tag{1.4}$$

We can also write $T$ in terms of $\omega$. Substituting (1.3) into (1.4) gives

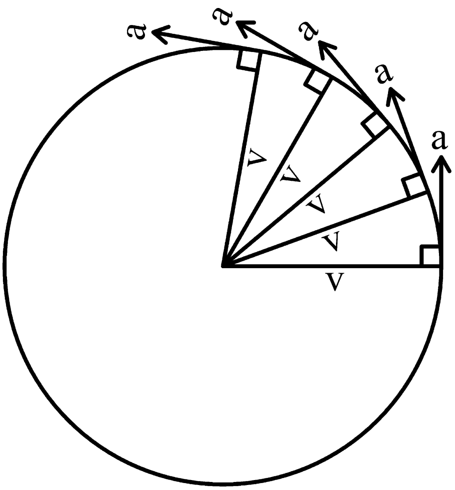


**Fig. 1.6.** The speed of the rotating point does not change, but its velocity does. This is because velocity has direction as well as magnitude. It is possible to imagine the velocity as the "radius" of a "circle of velocity."

$$\frac{T}{2\pi} = \frac{1}{\omega} = \frac{2\pi r}{2\pi v} = \frac{r}{v}. \tag{1.5}$$

There is a striking analogy between the circles of Figs. 1.4 and 1.6. In both cases, the time to complete once circumference is $T$. By direct analogy with (1.4),

$$\begin{aligned} \text{Acceleration} &= \frac{\text{Speed change}}{\text{Time}}; \\ \text{Time} &= \frac{\text{Speed change}}{\text{Acceleration}}; \\ \text{i.e.,}\quad T &= \frac{2\pi v}{a}. \end{aligned} \tag{1.6}$$

By analogy with (1.5)

$$\frac{T}{2\pi} = \frac{1}{\omega} = \frac{2\pi v}{2\pi a} = \frac{v}{a}. \tag{1.7}$$

Why did I do this? Because I can use (1.7) and (1.5) to figure out what the acceleration of a point going around in a circle is. Watch this. First I use (1.7) to get one formula for the acceleration, then I use (1.5) to get rid of the velocity term, which I do not really want.

$$a = \omega v = \omega(\omega r) = \omega^2 r. \tag{1.8}$$

A very important law in dynamics is Isaac Newton's second law of motion. This law is given in his book "Mathematical Principles of Natural Philosophy,"[4] although even the English translations of this Latin work look very old fashioned and strange to our eyes. In more modern language, Newton's second Law states that

$$F = ma, \tag{1.9}$$