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Richard Dodd
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1

Introduction

1.1 Using SI units in astronomy

The target audience for a book on using SI units in astronomy has to be astronomers who teach and/or carry out astronomical research at universities and government observatories (national or local) or privately run observatories. If this group would willingly accept the advantages to be gained by all astronomers using the same set of units and proceed to lead by example, then it should follow that the next generation of astronomers would be taught using the one set of units. Since many of the writers of popular articles in astronomy have received training in the science, non-technical reviews might then also be written using the one set of units. Given the commitment and competence of today's amateur astronomers and the high-quality astronomical equipment they often possess, it follows that they too would want to use the one set of units when publishing the results of their research.

As to why one set of units should be used, a brief search through recent astronomical literature provides an answer. Consider the many different ways the emergent flux of electromagnetic radiation emitted by celestial bodies and reported in the papers listed below and published since the year 2000, is given.

Józsa *et al*. (2009) derived a **brightness temperature of** $\mathbf{4 \times 10^5}$ **K** for a faint central compact source in the galaxy IC2497 observed at a radio frequency of **1.65 GHz**.

Bohlin & Gilliland (2004), using the Hubble Space Telescope to produce absolute spectrophotometry of the star Vega from the far ultraviolet (**170 nm**) to the infrared (**1010 nm**), plotted their results in $\mathbf{erg\,.\,cm^{-2}\,.\,s^{-1}\,.\,Å^{-1}}$ flux units.

Broadband **BVRI** photometric observations, listed as magnitudes, were made by Hohle *et al*. (2009) at the University Observatory Jena of OB stars in two nearby, young, open star clusters.

In the study of variable stars in the optical part of the spectrum it is quite common to use **differential magnitudes** where the difference in output flux between

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the variable object of interest and a standard non-varying star is plotted against time or phase (see, e.g., Yang, 2009).

An X-ray survey carried out by Albacete-Colombo *et al.* (2008) of low-mass stars in the young star cluster Trumpler 16, using the Chandra satellite, gives the median X-ray luminosity in units of $\mathbf{erg\,.\,s^{-1}}$.

The integral γ-ray photon flux above **0.1 GeV** from the pulsar J0205 + 6449 in SNR 3C58, measured with the Fermi gamma-ray space telescope, is given in units of $\mathbf{photons\,.\,cm^{-2}\,.\,s^{-1}}$ by Abdo *et al.* (2009).

These are just a few examples of the many different units used to specify flux. Radio astronomers and infrared astronomers often use janskys ($\mathbf{10^{-26}\,W\,.\,m^{2}\,.\,Hz^{-1}}$), whilst astronomers working in the ultraviolet part of the electromagnetic spectrum have been known to use flux units such as ($\mathbf{10^{-9}\,erg\,.\,cm^{-2}\,.\,s^{-1}\,.\,\AA^{-1}}$) and ($\mathbf{10^{-14}\,erg\,.\,s^{-1}\,.\,cm^{-2}\,.\,\AA^{-1}}$). So it would seem not unreasonable to conclude that whilst astronomers may well be mindful of SI units and the benefits of unit standardization they do not do much about it.

Among reasons cited in Cardarelli (2003) for using SI units are:

1. It is both metric (based on the metre) and decimal (base 10 numbering system).
2. Prefixes are used for sub-multiples and multiples of the units and fractions eliminated, which simplifies calculations.
3. Each physical quantity has a unique unit.
4. Derived SI units, some of which have their own name, are defined by simple expressions relating two or more base SI units.
5. The SI forms a coherent system by directly linking the mechanical, electrical, nuclear, chemical, thermodynamic and optical units.

A cursory glance at the examples given above shows numerous routes to possible mistakes. Consider the different powers of ten used, especially by ultraviolet astronomers. Some examples use wavelengths, some frequencies, and some energies to define passbands. One uses a form of temperature to record the flux detected. In short, obfuscation on a grand scale, which surely was not in the minds of the astronomers preparing the papers. For this book to prove successful it would need to assist in a movement towards the routine use of SI units by a majority, or at the very least a large minority, of astronomers.

1.2 Layout and structure of the book

The introductory chapter (1) contains the reasons for writing the book and the target audience, definitions of commonly used terms, a brief history of the standardization of scientific units of measurement and a short section on the future of SI units.

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Excerpt
More Information

Descriptions of the base and common derived SI units, plus acceptable non-SI units and IAU recommended units, are listed in Chapter 2 with Conférence Général des Poids et Mesures (CGPM) approved prefixes and unofficial prefixes for SI units with other possible alternatives.

Given the importance of the technique known as dimensional analysis to the study of units, an entire chapter (3) is allocated to the method, including worked examples. There are further examples throughout the book that illustrate the value of dimensional analysis in checking for consistency when transforming from one set of units to another.

Eight chapters (4–11) cover the seven SI base units plus the derived unit, the radian. Each includes the formal English language definition published by the Bureau International des Poids et Mesures (BIPM) and possible future changes to that definition. Examples of the uses of the unit are given, including transformations from other systems of units to the SI form. Derived units, their definitions, uses and transformations are also covered, with suitable astronomical worked examples provided. Each chapter ends with a summary and a short set of recommendations regarding the use of the SI unit or other International Astronomical Union (IAU) approved astronomical units.

The book ends with a chapter (12) on astronomical taxonomy, outlining various classification methods that are often of a qualitative rather than a quantitative nature (e.g., galaxy morphological typing, visual spectral classification).

The subject matter of the book covers almost all aspects of astronomy but is not intended as a textbook. Rather, it is a useful companion piece for an undergraduate or postgraduate student or research worker in astronomy, whether amateur or professional, and for the writers of popular astronomical articles who wish to link everyday units of measurement with SI units.

1.3 Definitions of terms (lexicological, mathematical and statistical)

The meaning of a word is, unfortunately, often a function of time and location and is prone to misuse, rather as Humpty Dumpty said in *Through the Looking Glass*, 'When I use a word, it means just what I chose it to mean – neither more nor less.'[3]

When discussing a subject such as the standardization of units, it is of paramount importance to define the terms being used. Hence, words that appear regularly throughout the book related to units and/or their standardization are listed in this section with the formal definition, either in their entirety or in part, as given in

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[3] See Carroll L. (1965). *Through the Looking Glass*. In *The Works of Lewis Carroll*. London: Paul Hamlyn, p. 174.

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Excerpt
More Information

volumes I and II of *Funk & Wagnalls New Standard Dictionary of the English Language* (1946).

1.3.1 Lexicological and mathematical

Unit

Any given quantity with which others of the same kind are compared for the purposes of measurement and in terms of which their magnitude is stated; a quantity whose measure is represented by the number 1; specifically in arithmetic, that number itself; unity. The numerical value of a concrete quantity is expressed by stating how many units, or what part or parts of a unit, the quantity contains.

Standard

Any measure of extent, quantity, quality, or value established by general usage and consent; a weight, vessel, instrument, or device sanctioned or used as a definite unit, as a value, dimension, time, or quality, by reference to which other measuring instruments may be constructed and tested or regulated.

The difference between a unit and a standard is that the former is fixed by definition and is independent of physical conditions, whereas a standard, such as the one-metre platinum–iridium rod held at the Bureau International des Poids et Mesures (BIPM) in Sèvres, Paris, is a physical realization of a unit whose length is dependent on physical conditions (e.g., temperature).

Quantity (Specific)

(1) Physics: A property, quality, cause, or result varying in degree and measurable by comparison with a standard of the same kind called a unit, such as length, volume, mass, force or work.
(2) Mathematics: One of a system or series of objects having only such relations, as of number or extension as can be expressed by mathematical symbols; also, the figure or other symbol standard for such an object. Mathematical quantities in general may be real or imaginary, discrete or continuous.

Measurement

The act of measuring; mensuration; hence, computation; determination by judgement or comparison. The ascertained result of measuring; the dimensions, size, capacity, or amount, as determined by measuring.

The mathematical definition of a quantity Q, is the product of a unit U, and a measurement m, i.e.,

$$Q = m\,U \tag{1.1}$$

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Excerpt
More Information

Q is independent of the unit used to express it. Units may be manipulated as algebraic entities (see Chapter 3) and multiplied and divided.

Dimension

Any measurable extent or magnitude, as of a line, surface, or solid; especially one of the three measurements (length, width and height) by means of which the contents of a cubic body are determined; generally used in the plural. Any quantity, as length, time, or mass, employed or regarded as a fundamental factor in determining the units of other physical quantities (see Chapter 3); as, the dimensions of velocity are length divided by time. The dimension of a physical quantity is the set containing all the units which may be used to express it, e.g., the dimension of mass is the set (kilogram, gram, pound, ton, stone, hundredweight, grain, solar mass . . .).

Accurate

Conforming exactly to truth or to a standard; characterized by exactness; free from error or defect; precise; exact; correct.

Accuracy

The state or quality of being accurate; exactness; correctness.

Precise

Having no appreciable error; performing required operations with great exactness.

Precision

The quality or state of being precise; accuracy of limitation, definition, or adjustment.

There is a tendency to use *accuracy* and *precision* as though they had the same meaning, this is not so. Accuracy may be thought of as how close the average value (see below) of the set of measurements is to what may be called the correct or actual value, and precision is a measure (see standard deviation below) of the internal consistency of the set of measurements. So if, for example, a measuring instrument is incorrectly set up so that it introduces a systematic bias in its measurements, these measures may well have a high internal consistency, and hence a high precision, but a low accuracy due to the instrumental bias.

Error

The difference between the actual and the observed or calculated value of a quantity.

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Excerpt
More Information

Mistake

The act of taking something to be other than it is; an error in action, judgement or perception; a wrong apprehension or opinion; an unintentional wrong act or step; a blunder or fault; an inaccuracy; as a mistake in calculation.

1.3.2 Statistical

Statistics is an extensive branch of mathematics that is regularly used in astronomy (see Wall & Jenkins, 2003). As a very basic introduction to simple statistics, definitions are given for the terms *mean* and *standard deviation*, which are commonly used by astronomers and an illustration (Figure 1.1) of the Gaussian or normal distribution curve showing how a set of random determinations of a measurement are distributed about their mean value.

Mean

Consider a set of N independent measurements of the value of some parameter x then the mean, or average, value, μ, is defined as:

$$\mu = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{1.2}$$

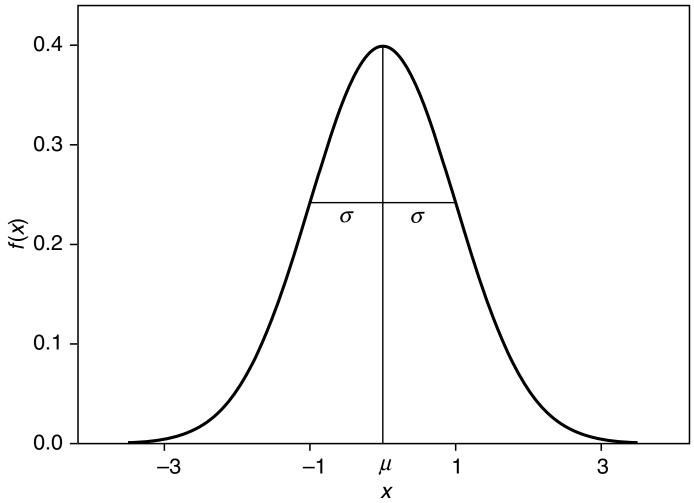

Figure 1.1. A Gaussian distribution with $\mu = 0$ and $\sigma = 1$ generated using equation (1.4).

Standard deviation

Given the same set of N measurements as above, the standard deviation, σ, is defined as:

$$\sigma = \frac{1}{N}\sqrt{\sum_{i=1}^{N}(x_i - \mu)^2} \tag{1.3}$$

Gaussian distribution

For large values of N, the expression describing the Gaussian or Normal distribution of randomly distributed values of x about their mean value μ is:

$$f(x) = \frac{1}{\sigma\sqrt{(2\pi)}} e^{\left(\frac{-1}{2\sigma^2}(x-\mu)^2\right)} \tag{1.4}$$

Figure 1.1 shows the typically bell shaped Gaussian distribution with a mean value, $\mu = 0$, and standard deviation, $\sigma = 1$.

Occasionally published papers may be found that use expressions such as *standard error* or *probable error*. If definitions do not accompany such expressions then they should be treated with caution, since different meanings may be attributed by different authors.

1.4 A brief history of the standardization of units in general

The history of the development of measurement units is well covered in many excellent books that range from those for children, such as Peter Patilla's *Measuring Up Size* (2000) and the lighthearted approach of Warwick Cairns in *About the Size of It* (2007), to the scholarly and comprehensive *Encyclopaedia of Scientific Units, Weights and Measures* by François Cardarelli (2003), and Ken Alder's detailed account of the original determination of the metre in the late eighteenth century, *The Measure of All Things* (2004).

Everyday units in common use from earliest times included lengths based on human anatomy, such as the length of a man's foot, the width of a hand, the width of a thumb, the length of a leg from the ground to the hip joint, and the full extent of the outstretched arms. Greater distances could be estimated by, e.g., noting the number of paces taken in walking from town A to town B. Crude standard weights were provided by a grain of barley, a stone and a handful of fruit. Early measures of dry and liquid capacity used natural objects as containers, such as gourds, large bird eggs and sea shells. Given that many such units were either qualitative or dependent on whose body was being used (e.g., King Henry I of England decreed in 1120 that the yard should be the distance from the tip of his nose to the end of

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More Information

his outstretched arm), trading from one village to another could be fraught with difficulties and even lead to violent altercations.

One of the earliest records of attempted standardization to assist in trade is set out in the Hebrew Bible in Leviticus, 19, 35–36 (Moffatt, 1950): ‘You must never act dishonestly, in court, or in commerce, as you use measures of length, weight, or capacity; you must have accurate balances, accurate weights, and an honest measure for bushels and gallons.’

Around 2000 years later, King John of England and his noblemen inserted a clause in the Magna Carta (number 35 on the Salisbury Cathedral copy of the document) that stated (in translation from the original abbreviated Latin text): ‘Let there be throughout our kingdom a single measure for wine and for ale and for corn, namely: the London quarter,[4] and a single width of cloth (whether dyed, russet or halberjet)[5] namely two ells within the selvedges; and let it be the same with weights as with measures.’

It would appear to be very difficult to introduce a new set of standard units by legislation. Even the French, under Emperor Napoleon I, preferred a mainly non-decimal system, which had more than 250 000 different weights and measures with 800 different names, to the elegant simplicity of the decimal metric system. This preference caused Napoleon to repeal the act governing the use of the metric system (passed by the republican French National Assembly in 1795, instituting the Système Métrique Décimal) and allowing the return to the *ancien régime* in 1812. The metric system finally won out in 1837 when use of the units was made compulsory. One hundred and sixty years later it was the turn of the British to object to the introduction of the metric system, despite such a change greatly simplifying calculations using both distance and weight measurements.

1.5 A brief history of the standardization of scientific units

With the beginnings of modern scientific measurements in the seventeenth century, the scientists of the time began to appreciate the value and need for a standardized set of well-defined measurement units.

The first step towards a non-anthropocentric measurement system was proposed by the Abbé Gabriel Mouton, who in 1670 put forward the idea of a unit of length (which he named the *milliare*) equal to one thousandth of a minute of arc along the North–South meridian line. Mouton may fairly be considered the originator of the metric system, in that he also proposed three multiple and three submultiple units based on the milliare but differing by factors of ten, which were named by

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[4] The London quarter was a measure that King Edward I of England decreed, in 1296, to be exactly eight striked bushels, where ‘striked’ implied the measuring container was full to the brim.

[5] ‘halberjet’ is an obsolete term for a type of cloth (Funk *et al.*, 1946).

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Excerpt
More Information

adding prefixes to milliare. The premature death of Mouton prevented him from developing his work further.

The English architect and mathematician Sir Christopher Wren proposed in 1667 using the length of the seconds pendulum as a fixed standard, an idea that was supported by the French astronomer Abbé Jean Picard in 1671, the Dutch astronomer Christiaan Huygens in 1673 and the French geodesist Charles Marie de la Condamine in 1746. Neither the milliare nor the length of the seconds pendulum was chosen to be the standard of length however, with that honour going to a measurement of length based on a particular fraction of the circumference of the Earth.

The metre, as the new unit of length was named, was originally defined as one ten millionth part of the distance from the North Pole to the Equator along a line that ran from Dunkirk through Paris to Barcelona. The survey of this line was carried out under the direction of P. F. E. Méchain and J. B. J. Delambre. Both were astronomers by profession, who took from 1792 to 1799 to complete the task. A comparison with modern satellite measurements produces a difference of 0.02%, with the original determined metre being 0.2 mm too short (Alder, 2004). A platinum rod was made equal in length to the metre determined from the survey and deposited in the Archives de la République in Paris. It was accompanied by a one-kilogram mass of platinum, as the standard unit of mass, in the first step towards the establishment of the present set of SI units. Following the establishment of the Conférence Général des Poids et Mesures (CGPM) in 1875, construction of new platinum–iridium alloy standards for the metre and kilogram were begun.

The definition of the metre based on the 1889 international prototype was replaced in 1960 by one based upon the wavelength of krypton 86 radiation, which in turn was replaced in 1983 by the current definition based on the length of the path travelled by light, in vacuo, during a time interval of 1/(299 792 458) of a second.

The unit of time, the second, initially defined as 1/(86 400) of a mean solar day was refined in 1956 to be 1/(31 556 925.974 7) of the tropical year for 1900 January 0 at 12 h ET (Ephemeris Time). This astronomical definition was superseded by 1968, when the SI second was specified in terms of the duration of 9 192 631 770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the caesium 133 atom at a thermodynamic temperature of 0 K.

The unit of mass (kilogram) is the only SI unit still defined in terms of a manufactured article, in this case the international prototype of the kilogram which, with the metre, were sanctioned by the first Conférence Général des Poids et Mesures (CGPM) in 1889. These joined the astronomically determined second to form the basis of the mks (metre–kilogram–second) system, which was similar to the cgs (centimetre–gram–second) system proposed in 1874 by the British Association for the Advancement of Science.

A move to incorporate the measurement of other physical phenomena into the metric system was begun by Gauss with absolute measurements of the Earth's magnetic field using the millimetre, gram and second. Later, collaborating with Weber, Gauss extended these measures to include the study of electricity. Their work was further extended in the 1860s by Maxwell and Thomson and others working through the British Association for the Advancement of Science (BAAS). Ideas that were incorporated at this time include the use of unit-name prefixes from micro to mega to signify decimal submultiples or multiples.

In the fields of electricity and magnetism, the base units in the cgs system proved too small and, in the 1880s, the BAAS and the International Electrotechnical Commission produced a set of *practical units*, which include the ohm (resistance), the ampere (electric current) and the volt (electromotive force). The cgs system for electricity and magnetism eventually evolved into three subsystems: esu (electrostatic), emu (electromagnetic) and practical. This separation introduced unwanted complications, with the need to convert from one subset of units to another.

This difficulty was overcome in 1901 when Giorgi combined the mechanical units of the mks system with the practical electrical and magnetic units. Discussions at the 6th CGPM in 1921 and the 7th CGPM in 1927 with other interested international organizations led, in 1939, to the proposal of a four-unit system based on the metre, kilogram, second and ampere, which was approved by the CIPM in 1946.

Eight years later at the 10th CGPM, the ampere (electric current), kelvin (thermodynamic temperature) and candela (luminous intensity) were introduced as base units. The full set of six units was named the *Système International d'Unités* by the 11th CGPM in 1960. The final base unit in the current set, the mole (amount of substance), was added at the 14th CGPM in 1971.

The task of ensuring the worldwide unification of physical measurements was given to the Bureau International des Poids et Mesures (BIPM) when it was established by the 1875 meeting of the Convention du Mètre. Seventeen states signed the original establishment document. The functions of the BIPM are as follows:

1. Establish fundamental standards and scales for the measurement of the principal physical quantities and maintain the international prototypes.
2. Carry out comparisons of national and international prototypes.
3. Ensure the coordination of corresponding measuring techniques.
4. Carry out and coordinate measurements of the fundamental physical constants relevant to these activities.

This brief enables the BIPM to make recommendations to the appropriate committees concerning any revisions of unit definitions that may be necessary.