

PHOTOMETRICS IN ASTRONOMY

BY

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ABSTRACT

The recent growth of astrophysics emphasizes the differences that exist between the photometric nomenclature of physics and that of astronomy. Astronomers employ such concepts as "brightness," "luminosity," and "magnitude"; but these same words are used with entirely different meanings by astronomers and by physicists. The paper shows how photometric concepts of the two groups can be correlated and made more precise.

1. INTRODUCTION

Each branch of science and technology develops concepts and units which, at their inception, seem most convenient in certain specialized calculations. Such a procedure is a natural one; and only when overlapping and interconnection of various fields occur, does this provincialism become troublesome. A familiar example is magnetic theory, which was developed independently from electric theory. Though Oersted showed in 1820 that the two subjects are interrelated, it is only within the last decade that the Giorgi mks system has freed us from the redundant sets of units that had plagued physicists for a century. Similarly, in astronomy we have "magnitude," "color index," and other ideas that are as unfamiliar to the physicist as his decibel system is to the astronomer.

The scientist is often accused of inventing an esoteric jargon that is meaningless to the uninitiated. This accusation is valid only if it places a barrier between one scientist and another. Certainly, it behooves all scientists to use the same nomenclature and employ the same units, even though the initial stages in such a unification may be burdensome.

One of the most glaring examples of poor standardization is the notation of photometrics, which has different nomenclature in astronomy, physics, meteorology, photography, and illuminating engineering. Too often attempts at standardization in this field have been left to the lighting-fixture salesman. The resulting definitions are of questionable value even for room lighting and are certainly inadequate for astrophysics.

In 1914, Herbert E. Ives published a noteworthy paper (1)³ outlining

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³ The boldface numbers in parentheses refer to the references appended to this paper.

a general system of radiometric and photometric concepts applicable to all of science and engineering. In the following pages, we have attempted to present a comprehensive system, somewhat similar to Ives' but taking into account the developments that have occurred during the intervening years.

2. PRINCIPAL CONCEPTS

A logical system (2) of active concepts is listed in Table I. The basic quantity may be taken as radiant power or *radiant pharos*, ex-

TABLE I.—*Principal Concepts of Radiometry and Photometry.*

RADIOMETRIC CONCEPTS				PHOTOMETRIC CONCEPTS			
Symbol	Name	Dimensions	Unit	Symbol	Name	Dimensions	Unit
F_r	Radiant pharos (radiant power)	$[P]$	watt	F	Luminous pharos (luminous flux)	$[F]$	lumen
D_r	Radiant pharosage	$[PL_r^{-2}]$	watt m ⁻²	D	Luminous pharosage	$[FL_r^{-2}]$	lumen m ⁻²
Q_r	Radiant phos	$[PT]$	watt sec	Q	Luminous phos	$[FT]$	lumen sec
U_r	Radiant phosage	$[PTL_r^{-2}]$	watt sec m ⁻²	U	Luminous phosage	$[FTL_r^{-2}]$	lumen sec m ⁻²
H_r	Radiant helios	$[PL_r^{-2}L_r^2]$	herschel	H	Luminous helios	$[FL_r^{-2}L_r^2]$	blondel
G_r	Radiant heliosent	$[PL_r^{-2}L_r]$	herschel m ⁻¹	G	Luminous heliosent	$[FL_r^{-2}L_r]$	blondel m ⁻¹
$J(\lambda)$	Phengosage	$[PL_r^{-2}\Lambda^{-1}]$	watt m ⁻² micron ⁻¹				

$\overbrace{\quad\quad\quad\quad\quad\quad\quad\quad\quad}^{\bar{J}(\lambda) \text{ Spectral lamprosity}}$

pressed in *watts*. The quantity measured by bolometer or radiation thermocouple is *radiant pharosage*,⁴ which is defined as radiant power per unit area. The mks (meter-kilogram-second) system of units is used, in accordance with modern trends in physics and electrical engineering (3).

Helios and *heliosent* are useful in the consideration of scattering and absorbing media; in the earth's atmosphere, for instance, or in the astrophysics of stellar interiors. The helios, at a point P in space and in a given direction, is defined as π times the pharosage at P , per unit solid angle (4):

$$H_r = \pi \lim_{\Omega \rightarrow 0} \frac{D_r}{\Omega} \quad (1)$$

where Ω is the solid angle whose apex is at P and whose axis is in the given direction. *Heliosent* is the helios contributed by a radiating medium, per unit thickness:

$$G_r = \frac{dH_r}{dl}. \quad (2)$$

Helios and heliosent are scalar functions of position and direction; but pharosage may be considered, if desired, as a vector, thus allowing the use of vector field theory (5).

⁴ Pronounced *far o sash'*. The *-age* ending indicates "per unit area," just as *-ent* means "per unit distance," *-or* indicates a device, and *-ance* indicates a property of a device.

Physical measurements ordinarily deal with power rather than with energy. Thus it is convenient to employ radiant pharos F_r and the geometrically related concepts D_r , H_r , and G_r . In some cases, however, the use of energy may be desirable instead of power. Then *phos* and *phosage* are used.

A radiation thermocouple or a bolometer placed at the exit slit of a monochromator allows the measurement of radiant pharos per unit wavelength band. This characteristic of a continuous spectrum may be called the *phengosage* $J(\lambda)$ and may be expressed in watt m^{-2} micron $^{-1}$. The total pharosage is

$$D_r = \int_0^{\infty} J(\lambda) d\lambda. \quad (3)$$

This completes our brief survey of radiometric concepts. If a selective receptor (the eye, the photocell, or the photographic plate) is employed instead of a non-selective receptor, the values of $J(\lambda)$ must be weighted with respect to a response function $w(\lambda)$ for the particular receptor (6). Then, in place of Eq. 3, we have for the total response:

$$D = \int_0^{\infty} w(\lambda) \cdot J(\lambda) d\lambda. \quad (4)$$

Here D can no longer be expressed in watt m^{-2} : it requires a new unit for each weighting function.

If $w(\lambda)$ represents the response curve for a photocell (amperes per watt m^{-2}), then D is the current (amp.) produced by the cell. If $w(\lambda)$ represents the relative sensitivity of a photographic emulsion, then D expresses the radiation evaluated with respect to this receptor. But the most useful weighting function is the one for the light-adapted eye (7) (C.I.E. lamprosity function $\bar{y}(\lambda)$). When this internationally standardized weighting function is used in Eq. 4, D is called *luminous pharosage* ("luminous flux density," "illumination"), which may be taken as the basis for a whole set of *photometric concepts* (Table I).

Note the close parallelism between radiometric and photometric columns of Table I. The same symbols are employed in both columns, with subscripts r and l to distinguish between radiometric and photometric quantities. When we are dealing with a single system, subscripts can be omitted without ambiguity. Also, the names of concepts are the same in both columns, except for the adjectives "radiant" and "luminous." Dimensions are also parallel, one set being based on radiant pharos [P] and the other on luminous pharos [F]. Two distance dimensions—radial [L_r] and tangential [L_t]—are needed to make the specification unique (8).

By employing Eq. 4 with other weighting functions, we can derive various sets of concepts parallel to those of Table I. The use of an average curve $w(\lambda)$, for a type of photographic plate commonly used in

astronomy, gives photographic concepts F_p , D_p , Q_p , U_p , H_p , and G_p . Another set of concepts utilizes the curve for the dark-adapted eye (rod vision), which gives quantities suitable for work with large, dark objects at very low values of helios (9).

In the visual observation of stars, satisfactory results are obtained most frequently when the star is imaged on the fovea. And the fovea contains no rods. Thus the weighting function for cone vision should be useful in astronomy. Apparently the C.I.E. weighting function is satisfactory here, just as it is in so many other applications of light. The systems of Table I therefore remain the two most important of the many possible parallel systems. Even *photographic* measurements can be made in terms of lumens by the use of panchromatic plates with green filters; and suitable filters allow *photocells* also to be corrected to the lumen basis. It would seem that astronomers might simplify their calculations by the more frequent use of color-corrected photography, thereby eliminating "photographic magnitudes."

Examination of Table I shows that our nomenclature is not in complete agreement with any of the systems developed by illuminating engineers (10). The purpose of our study (2), extending over a period of 16 years, has been to develop a nomenclature that is completely general so that it can be employed in all calculations of light (11). Advantages are

- (a) Maximum generality. Elimination of specialized ideas like "candlepower" and "brightness," which are of limited applicability.
- (b) Parallel arrangement of radiometric and photometric quantities. Can be extended to any other response curves.
- (c) International names. Unambiguous. Can be incorporated into any language without translation (12).

3. A SIMPLIFIED SYSTEM

In most astronomical work, the full set of concepts (Table I) is not needed. In fact there is advantage in limiting ourselves, whenever possible, to

- (1) Luminous pharosage D ,
- (2) Luminous pharos F .

Pharosage will be expressed in *lumens per square meter* and pharos in *lumens*. It is convenient to express these quantities also on a logarithmic scale.

Pharosage and pharos meet the two most frequent needs in astronomical photometrics:

- (1) the need for a measure of the light received on the earth from a star, and
- (2) the need for a measure of the intrinsic strength of the source.

The first need is met by specifying the incident lumens per square meter

received at the earth from the given star. The value is measured on a surface that is perpendicular to the direction of propagation of radiant energy; and this value should be corrected for the effect of the earth's atmosphere. Then D represents the true luminous pharosage outside the atmosphere, independent of atmospheric conditions, elevation of the observatory, or zenith angle of the star. The quantity which we call *pharosage* is usually called "brightness" by astronomers. Such a use of the term "brightness" is unfortunate, since it is completely at variance with accepted meanings (10).

Experience shows that logarithmic quantities are useful in astronomical calculations. Pharosage can be expressed logarithmically, giving *magnitude* m . According to Russell (13),

$$m = -2.500 \log D - 14.18, \quad (5)$$

where D is the incident pharosage in lumen m^{-2} . The difference in magnitude of two stars is therefore

$$m_1 - m_2 = 2.500 \log (D_2/D_1). \quad (6)$$

Also, from Eq. 5, the pharosage corresponding to a given magnitude is

$$D = 2.128 \times 10^{-6} (10)^{-0.400m}. \quad (7)$$

It is interesting to compare the concept of stellar magnitude with a logarithmic relation that has become important in acoustics and electricity. The *decibel* difference between two values of pharosage is defined as

$$(D_1)_{db} - (D_2)_{db} = 10 \log (D_1/D_2). \quad (8)$$

The zero of the decibel scale can be placed anywhere; but a convenient location is at the absolute threshold of the eye. Taking threshold pharosage as

$$D_{\min} = 6.78 \times 10^{-9} \text{ lumen m}^{-2},$$

and atmospheric transmission as 0.80, we have as decibel specification of pharosage:

$$(D)_{db} = 10 \log D + 80.73. \quad (5a)$$

Also,

$$D = 8.45 \times 10^{-9} (10)^{0.1(D)_{db}}. \quad (7a)$$

Comparison of Eqs. 5 and 5a shows that

(i) The scales of magnitude and decibels run in opposite directions. A large magnitude is associated with small pharosage: a large decibel value means large pharosage.

(ii) Each step in the decibel scale is exactly one-quarter of a step in

the magnitude scale. Thus *a difference of one magnitude is exactly equal to a difference of 4.00 decibels*. The conversion factor is

$$(D)_{db} = 24.0 - 4.00m. \quad (9)$$

Some values of $(D)_{db}$ and m are listed in Table II.

TABLE II.—*Some Conspicuous Stars.*
(Values apply outside the earth's atmosphere)

Name	D (lumen m^{-2})	$(D)_{db}$	m
Sun	1.29×10^5	131.8	-26.96
α Canis Majoris	9.12×10^{-6}	30.3	-1.58
α Lyrae	1.87×10^{-6}	23.4	+0.14
α Boötis	1.71×10^{-6}	23.0	0.24
α Eridani	1.22×10^{-6}	21.6	0.60
β Centauri	9.64×10^{-7}	20.6	0.86
α Aquilae	9.38×10^{-7}	20.4	0.89
β Geminorum	6.98×10^{-7}	19.2	1.21
α Cygni	6.25×10^{-7}	18.7	1.33
β Crucis	5.35×10^{-7}	18.0	1.50

Note.—Luminous pharosage D is for a surface that is perpendicular to the light rays, at the earth but outside the earth's atmosphere.

Though the astronomer may not wish to give up such a time-honored idea as stellar magnitude, he will find that all its advantages are contained in the decibel specification; and the latter is more closely related to the other sciences. The rapidly growing use of physical photometry brings astronomy, physics, and electrical engineering ever closer together. So it becomes increasingly important that experts in all these fields learn to use the same scientific language. Table III

TABLE III.—*Range of Astronomical Photometrics.*
(Values apply outside the earth's atmosphere)

D (lumen m^{-2})	$(D)_{db}$	Magnitude m
1.29×10^5 (Sun)	131.8	-26.96
9.12×10^{-6} (Sirius)	30.3	-1.58
1.71×10^{-6}	23.0	+0.24
8.47×10^{-7}	20.0	1.0
3.37×10^{-7}	16.0	2.0
5.35×10^{-8}	8.0	4.0
8.47×10^{-9}	0.0	6.0
2.13×10^{-10}	-16.0	10.0
2.13×10^{-2}	-36.0	15.0
8.47×10^{-15}	-60.0	21.0

indicates the range of astronomical photometrics, expressed in lumen m^{-2} , decibels, and magnitudes.

As an illustration of the use of the foregoing equations, consider the light received from the sun. The solar pharosage outside the earth's atmosphere may be taken as 129,000 lumen m^{-2} . From Eq. 5a, we find that the corresponding value is 131.8 db above threshold. This is analogous to the same number of db in acoustics, which specifies a painfully loud sound.

What are D and m corresponding to visual threshold? For threshold, $(D)_{db} = 0$, so from Eqs. 7a and 9,

$$\begin{cases} D = 8.45 \times 10^{-8} \text{ lumen } m^{-2}, \\ m = \frac{1}{4}(24.0 - 0) = 6.0. \end{cases}$$

The faintest star that can be detected photographically with a 100-in. reflector is of about the 21st magnitude. From Eq. 9, this corresponds to

$$(D)_{db} = -60$$

or 60 db below the threshold of the unaided eye. The value of pharosage, outside the earth's atmosphere, produced by a star of magnitude 21, is

$$\begin{aligned} D &= 8.45 \times 10^{-8} (10)^{-6.0} \\ &= 8.45 \times 10^{-18} \text{ lumen } m^{-2}. \end{aligned}$$

The second photometric requirement of astronomy is a way of specifying the intrinsic output of a star. The simplest concept that applies here seems to be *total pharos* F_s , expressed in *lumens* and based on the assumption of uniform radiation in all directions. This quantity can replace the rather vague astronomical concept called "luminosity."

The total pharos F_s from a uniform star is

$$F_s = 4\pi l^2 D, \quad (10)$$

where F_s is in *lumens*, D is in *lumen m^{-2}* outside the earth's atmosphere, and l is the distance from star to earth, measured in meters. If l is expressed in lightyears, Eq. 10 becomes

$$F_s = 1.125 \times 10^{33} l^2 D. \quad (10a)$$

A logarithmic designation may be used with F_s , just as with D . *Absolute magnitude* M is such a designation:

$$M = m + 5.00 \log (32.58/l), \quad (11)$$

where l is in lightyears. The corresponding decibel expression is

$$(F_s)_{db} = (D)_{db} + 20 \log (l/32.58), \quad (12)$$

and the relation between pharos (in db) and absolute magnitude is

$$(F_s)_{db} = 24.0 - 4.00M. \quad (13)$$

Values of pharos for a few stars are given in Table IV.

TABLE IV.—*Luminous Output.*

Name	Distance (lightyears)	F_s (lumens)	$(F_s)_{db}$	M
Sun	1.581×10^{-5}	3.63×10^{28}	5.5	+4.6
α Canis Majoris	8.8	7.92×10^{29}	18.9	+1.3
α Lyrae	26.2	1.48×10^{30}	21.6	+0.6
α Boötis	40.8	3.16×10^{30}	24.9	-0.2
α Eridani	66.5	6.15×10^{30}	27.8	-0.9
β Centauri	296	9.75×10^{31}	39.8	-4.0
α Aquilae	16.0	2.69×10^{29}	14.2	+2.4
β Geminorum	32.3	8.28×10^{29}	19.1	+1.2
α Cygni	650	3.02×10^{32}	44.7	-5.2
β Crucis	204	2.51×10^{31}	33.9	-2.5

For instance, Nova Aquilae increased from $m = 18$ on June 5, 1918 to $m = -0.5$ on June 9. Expressed in decibels this change is

$$18.5(4.00) = 74.0 \text{ db},$$

corresponding to a pharos ratio of 2.5×10^7 . Using an estimated distance of 1000 lightyears, we find for the maximum luminous output of Nova Aquilae,

$$(F_s)_{db} = 26.0 + 20 \log (1000/32.58) = 55.7 \text{ db}.$$

This is about 50 db above the luminous output of the sun. Indeed,

$$\begin{aligned} (F_s)_{db} - (F_\odot)_{db} &= 10 \log (F_s/F_\odot) \\ &= 55.7 - 5.5 = 50.2 \text{ db}, \end{aligned}$$

or

$$F_s/F_\odot = 104,800.$$

Since $F_\odot = 3.63 \times 10^{28}$ lumen, the maximum pharos of Nova Aquilae was

$$F_s = 104,800(3.63 \times 10^{28}) = 3.80 \times 10^{33} \text{ lumens}.$$

4. DISTANCE

Photometry is useful also in the measurement of astronomical distance. For a parallax of less than about $0''.010$, the computed distances are so inaccurate as to be almost meaningless. The cepheids can then be employed to obtain the approximate distance. According to Shapley (14), the mean absolute magnitude \bar{M} of a cepheid is related to its period by the empirical equation,

$$\bar{M} = -0.28 - 1.74 \log \tau, \quad (14)$$

where τ is the period in days. The distance (lightyears) is then

$$l = 32.58(10)^{0.200(\bar{m} - \bar{M})}, \quad (15)$$

where \bar{m} is the mean magnitude measured at the earth.

Expressed in decibels, we have

$$(\bar{F}_s)_{db} = 25.12 + 6.96 \log \tau \quad (16)$$

and

$$l = 32.58(10)^{0.5[(F_s)_{db} - (D)_{db}]}. \quad (17)$$

For still greater distances, where the individual stars cannot be resolved and where only the galaxies can be seen, an estimate of distance can be made by considering the total pharos of a galaxy as (14)

$$(F_s)_{db} = 86.8 \text{ db}, \quad \text{or} \quad M = -15.2.$$

Distance can then be obtained from Eq. 15 or Eq. 17.

For example, the cepheid ξ Geminorum has a period of 10.15 days and the mean pharosage at the earth is 8.0 db above threshold. From Eq. 16,

$$(\bar{F}_s)_{db} = 25.12 + 6.96 \log 10.15 = 32.12.$$

From Eq. 17, the distance to ξ Geminorum is

$$l = 32.58(10)^{0.06[32.12-8.00]} = 524 \text{ lightyears.}$$

The faintest objects that can be photographed with a 100-in. telescope are approximately 60 db below threshold. Assuming that one of the objects is an average galaxy with

$$(\bar{F}_s)_{db} = 86.8,$$

we find the distance

$$l = 32.58(10)^{0.06[86.8+60.0]} = 7.1 \times 10^8 \text{ lightyears.}$$

TABLE V.—*A Comparison of Nomenclature.*

Physical Specification			Astronomical Specification		
D	Pharosage	lumen m^{-2}			“Brightness”
$(D)_{db}$	Pharosage	db	m	Magnitude	
$(D)_{db} = 10 \log D + 80.73$			$m = -2.5000 \log D - 14.18$		
F_s	Pharos	lumen	L	“Luminosity”	
$(F_s)_{db}$	Pharos	db	M	Absolute magnitude	
$(F_s)_{db} = (D)_{db} + 20 \log (l/32.58)$			$M = m + 5.00 \log (32.58/l)$		

5. COLOR OF STARS

Methods of color measurement for stars are still in a very unsatisfactory state. This is understandable in view of the difficulties of spectroradiometry at low values of pharosage. Future developments of physical receptors will probably help matters; but it is quite likely that the subject can be dealt with more precisely even today.

The best system of color specification is undoubtedly the C.I.E. trichromatic system (7). The spectral distribution, $J(\lambda) \text{ vs } \lambda$, is measured for the star; and the standard weighting functions $\bar{x}(\lambda)$; $\bar{y}(\lambda)$; $\bar{z}(\lambda)$ are employed, giving the trichromatic specification

$$\left. \begin{aligned} X &= \int_0^{\infty} \bar{x}(\lambda) \cdot J(\lambda) d\lambda, \\ Y &= \int_0^{\infty} \bar{y}(\lambda) \cdot J(\lambda) d\lambda, \\ Z &= \int_0^{\infty} \bar{z}(\lambda) \cdot J(\lambda) d\lambda. \end{aligned} \right\} \quad (18)$$

These integrated values can be obtained analytically from the $J(\lambda)$ -curve, or they can be measured directly by employing three calibrated filters with photocells or with photographic plates. The latter method (trichromatic colorimeter) requires no spectroradiometer and is therefore suitable for stellar measurements.

The three numbers (X , Y , Z), obtained in either way, may be regarded as the coordinates of a point in color 3-space. Useful also are the homogeneous coordinates in a color 2-space:

$$\left. \begin{aligned} x &= \frac{X}{X + Y + Z}, \\ y &= \frac{Y}{X + Y + Z}. \end{aligned} \right\} \quad (19)$$

Each quality of color is uniquely represented by a distinct point in the color triangle.

The advantage of the C.I.E. system is that it applies to any radiator and is not limited to non-selective or Planckian radiation. If the radiation is really Planckian, points lie on a single curve (Planckian locus) in the color diagram, and specification requires only one number instead of two. This number is usually taken as the *temperature*. But spectro-radiometric curves for the sun and for some stars exhibit rather large deviations from a Planckian curve. Thus the designation of star color by temperature is a rather crude approximation which should preferably be replaced by the trichromatic specification.

Color temperature T_c is usually determined from visual and photographic magnitudes or from visual and bolometric magnitudes. Probably a more accurate determination can be made by using one receptor with two colored filters, say a red and a blue. The ratio of readings obtained with the two filters is a function of color temperature, and the calibration can be effected experimentally by means of a color-temperature standard lamp or can be calculated on the basis of Planck's equation. All these methods, however, suffer from the defect that a non-selective radiator is postulated. It is not surprising, therefore, that experimental values, obtained for a given star by different methods, often differ by a thousand degrees. Would it not be preferable to replace the two filters of the T_c -determination by *three* filters required for the trichromatic method, thus obtaining a true specification of color without assumption of blackbody radiation?

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