Calculating Stellar Distance, Luminosity, Radius, and Mass Using Only High School Physics Laws

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Abstract

The distance between stars and Earth, stellar luminosity, radius, and mass are important concepts in the study and research of stellar physics. We must know these parameters to better understand stars and even the entire universe. However, because stars are too distant from us, the physical properties of stars cannot be measured directly. It is precisely for this reason that many physical parameters of stars have been controversial in the astronomical community for many years. This paper does not attempt to use more advanced mathematical and physical formulas or methods to precisely and detailedly calculate stellar physical quantities, thereby resolving these controversies, because I believe that astronomy should be understandable to people with weak foundations in mathematics and physics. Therefore, this paper only uses high school physics laws to simply measure stellar distance, luminosity, radius, and mass.

Full Text

Preamble

The distance to stars, along with their luminosity, radius, and mass, represents a cornerstone of stellar physics research and education. These fundamental parameters are essential for understanding not only individual stars but the cosmos at large. However, direct measurement of stellar properties remains impossible due to their immense distances from Earth—a limitation that has left many stellar parameters subject to ongoing debate within the astronomical community. This paper does not attempt to resolve such controversies through sophisticated mathematical or physical techniques. Rather, it is founded on the principle that astronomy should remain accessible to those without advanced training in mathematics and physics. Accordingly, this work demonstrates how basic high school physical laws can be employed to estimate stellar distance, luminosity, radius, and mass.

Keywords: stellar distance; luminosity; radius; mass; gravitation; Kepler' s laws

1. Measuring Stellar Distance

Trigonometric parallax enables distance measurement for relatively nearby stars, with current technology having applied this method to approximately 100,000 stars. As Earth orbits the Sun, nearby stars exhibit apparent motion against the backdrop of more distant stars. Over the course of a year, stars perpendicular to Earth' s orbital plane (the ecliptic) trace circular paths on the sky, while stars lying in the ecliptic plane trace back-and-forth line segments. Stars at intermediate angles describe elliptical trajectories, with the angular size of the semi-major axis given by the geometry of Earth' s orbit.

The parsec (pc) constitutes a fundamental unit of length defined by this phenomenon. One parsec is defined as the distance at which the parallax angle equals exactly one arcsecond (1/3600 of a degree, or $\pi/(180\times3600)$ radians). Consequently, $1 pc = 2.1\times10^5 AU = 3.1\times10^{18} cm = 3.3 ly$. The light-year (ly), representing the distance light travels in vacuum in one year, provides another common u
$1 ly = 365.25\times24\times3600\times c = 3.15\times10^7$ s $\times$ 3×10^{10} cm/s. The nearest stars to our Solar System lie at distances of approximately 1 pc, while most stars visible to the naked eye are located within 100 pc. For more distant objects, astronomers employ kiloparsecs (kpc; 10^3 pc), megaparsecs (Mpc; 10^6 pc), and gigaparsecs (Gpc; 10^9 pc).

In addition to parallactic apparent motion, stars possess true motions relative to the Sun. On human timescales, these proper motions typically appear as constant-velocity linear drifts across the sky. Consequently, the parallactic motion of nearby stars is generally superimposed upon this linear proper motion, producing curled or wavy trajectories in observational data.

2. Measuring Stellar Luminosity and Radius

For stars with known distances and measured flux, the luminosity follows from the inverse-square law: $L = f4\pi d^2$. This quantity, integrated across all wavelengths, is termed the bolometric luminosity. If the temperature of the stellar photosphere is known, the stellar radius can be derived through the relation:

$L = 4\pi r$

Alternatively, when luminosity and radius are known, the temperature determined from this relationship is designated the effective temperature TE. The solar radius is $r = 7\times10^{10}$ cm. Contemporary stellar radii are generally measured through interferometric observations.

3. Measuring Stellar Mass

Direct mass measurement is generally possible only for stars in binary or multiple systems. A substantial fraction of all stars belong to binary systems—the Sun likely represents a rare exception among single-star systems. Observationally, binary systems are classified into several categories. Visual binaries consist of resolvable pairs where both components can be observed orbiting their common center of mass, though their orbital periods are often extremely long on human timescales. In astrometric binaries, periodic motion of one component about the system' s common center of mass can be detected even when the companion is too faint to observe directly. Eclipsing binaries contain unresolved pairs whose orbital planes are sufficiently inclined relative to our line of sight that each star periodically occults the other. Photometric monitoring reveals the binary nature through two brightness dips per orbital period, each corresponding to one star eclipsing the other, with depth determined by the relative sizes and luminosities of the components.

Spectroscopic binaries are spatially unresolved pairs whose dual nature is revealed through spectral analysis. The observed photospheric absorption spectrum may represent a superposition of two distinct stellar types, or orbital velocities may produce Doppler shifts $\Delta\lambda/\lambda = v/c$ sufficient to separate absorption lines from components of identical spectral type. These shifted lines oscillate periodically throughout each orbit. In some cases, one component may be too faint or lack strong absorption lines to be detected in the composite spectrum, yet its presence is betrayed by periodic Doppler shifts of the brighter star' s lines.

The determination of stellar mass in binary systems relies on orbital dynamics. Two stars of mass M1 and M2 execute elliptical orbits about their common center of mass. For the simplest case of circular orbits, the center of mass lies at a point between the stars where r1M1 = r2M2, with r1 and r2 representing distances to the center of mass. Defining a = r1 + r2 as the separation between masses, each component experiences mutual gravitational attraction and orbits the center of mass with angular frequency ω. The equation of motion for the first mass is:

M1ω^{2r1} =

where G is the gravitational constant. Combining these relations yields Kepler' s law:

1+ 2

Kepler' s law enables stellar mass determination, as demonstrated by the Sun-Earth system. With Earth' s mass negligible compared to the Sun' s, the solar mass becomes:

M = (4$\pi^{\{\{2a\}\}}$\{3)/(Gτ\}\}^2)

where $\tau = 2\pi/\omega$ is the orbital period (1 year). Expressed in cgs units, the solar mass is approximately 10^{33} g.

For visual binaries, direct measurement of angular separations 1 and 2 between each star and the common center of mass is possible. The orbital plane normal is typically inclined by angle i relative to our line of sight, projecting the circular orbit into an ellipse. Tracking most of the orbit resolves this complication, as the ellipse' s semi-major axis corresponds to the angular radius of the deprojected circular orbit. With both stars at distance d, the ratio of angles yields the mass ratio:

M1/M2 = 2/ 1

Given the distance (from which physical separation a can be derived) and observed period, Kepler' s law provides M1 + M2. Combined with the mass ratio, individual masses M1 and M2 can be solved uniquely.

In practice, many binary orbits are elliptical rather than circular. Elliptical orbits require two additional parameters—eccentricity and the orientation angle of the ellipse within the orbital plane (as viewed from Earth). However, these parameters can be determined from observational data, such as the shape of the sky projection, the functional form of radial velocity curves, or asymmetries in eclipse timing and duration. The fundamental principles and limitations of mass determination for circular binaries extend naturally to elliptical systems.

References

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Note: Figure translations are in progress. See original paper for figures.