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Barycenter

The **barycenter** (or **barycentre**; from the Ancient Greek βαρὺς *heavy* + κέντρον *centre*[1]) is the center of mass of two or more bodies that are orbiting each other, which is the point around which they both orbit. It is an important concept in fields such as astronomy and astrophysics. The distance from a body's center of mass to the barycenter can be calculated as a simple two-body problem.

In cases where one of the two objects is considerably more massive than the other (and relatively close), the barycenter will typically be located within the more massive object. Rather than appearing to orbit a common center of mass with the smaller body, the larger will simply be seen to wobble slightly. This is the case for the Earth–Moon system, where the barycenter is located on average 4,671 km (2,902 mi) from the Earth's center, well within the planet's radius of 6,378 km (3,963 mi). When the two bodies are of similar masses, the barycenter will generally be located between them and both bodies will follow an orbit around it. This is the case for Pluto and Charon, as well as for many binary asteroids and binary stars. When the less massive object is far away, the barycenter can be located outside the more massive object. This is the case for Jupiter and the Sun. Despite the thousandfold difference in mass, due to the relatively large distance between them, the barycenter is outside the Sun.[2]

In astronomy, **barycentric coordinates** are non-rotating coordinates with the origin at the center of mass of two or more bodies. The International Celestial Reference System is a barycentric one, based on the barycenter of the Solar System.

In geometry, the term "barycenter" is synonymous with centroid, the geometric center of a two-dimensional shape.

Contents

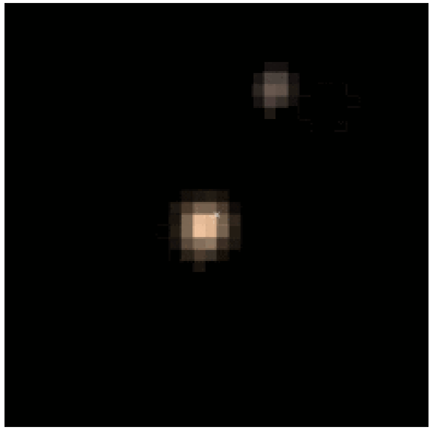
Two-body problem

The barycenter is one of the foci of the elliptical orbit of each body. This is an important concept in the fields of astronomy and astrophysics. If a is the distance between the centers of the two bodies (the semi-major axis of the system), r_1 is the semi-major axis of the primary's orbit around the barycenter, and $r_2 = a - r_1$ is the semi-major axis of the secondary's orbit. When the barycenter is located *within* the more massive body, that body will appear to "wobble" rather than to follow a discernible orbit. In a simple two-body case, r_1, the distance from the center of the primary to the barycenter is given by:

$$r_1 = a \cdot \frac{m_2}{m_1 + m_2} = \frac{a}{1 + \frac{m_1}{m_2}}$$

where :

r_1 is the distance from body 1 to the barycenter
a is the distance between the centers of the two bodies
m_1 and m_2 are the masses of the two bodies.



Barycentric view of the Pluto–Charon system as seen by *New Horizons*

Primary–secondary examples

The following table sets out some examples from the Solar System. Figures are given rounded to three significant figures. The term primary–secondary is used to distinguish between involved participants; with the larger called "the primary", and the smaller called "the secondary".

m_1 is the mass of the primary in Earth masses ($M_\oplus$)
m_2 is the mass of the secondary in Earth masses ($M_\oplus$)
a (km) is the average orbital distance between the two bodies
r_1 (km) is the distance from the center of the primary to the barycenter
R_1 (km) is the radius the primary
$\frac{r_1}{R_1}$ a value less than one means the barycenter lies inside the primary

Primary–secondary examples

Primary	m_1 ($M_\oplus$)	Secondary	m_2 ($M_\oplus$)	a (km)	r_1 (km)	R_1 (km)	$\frac{r_1}{R_1}$
Earth	1	Moon	0.0123	384,000	4,670	6,380	0.732[A]
Pluto	0.0021	Charon	0.000254 (0.121 M_P)	19,600	2,110	1,150	1.83[B]
Sun	333,000	Earth	1	150,000,000 (1 AU)	449	696,000	0.000646[C]
Sun	333,000	Jupiter	318 (0.000955 $M_\odot$)	778,000,000 (5.20 AU)	742,000	696,000	1.07[D]

A The Earth has a perceptible "wobble". Also see tides.
B Pluto and Charon are sometimes considered a binary system because their barycenter does not lie within either body.[3]
C The Sun's wobble is barely perceptible.
D The Sun orbits a barycenter just above its surface.[4]

Inside or outside the Sun?

If $m_1 \gg m_2$ — which is true for the Sun and any planet — then the ratio $\frac{r_1}{R_1}$ approximates to:

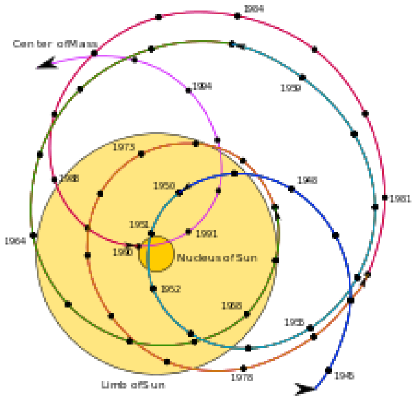
$$\frac{a}{R_1} \cdot \frac{m_2}{m_1}$$

Hence, the barycenter of the Sun–planet system will lie outside the Sun only if:

$$\frac{a}{R_\odot} \cdot \frac{m_{\text{planet}}}{m_\odot} > 1 \Rightarrow a \cdot m_{\text{planet}} > R_\odot \cdot m_\odot \approx 2.3 \times 10^{11}\ m_\oplus\ \text{km} \approx 1530\ m_\oplus\ \text{AU}$$

That is, where the planet is massive *and* far from the Sun.

If Jupiter had Mercury's orbit (57,900,000 km, 0.387 AU), the Sun–Jupiter barycenter would be approximately 55,000 km from the center of the Sun ($\frac{r_1}{R_1} \approx 0.08$). But even if the Earth had Eris' orbit (1.02×10^{10} km, 68 AU), the Sun–Earth barycenter would still be within the Sun (just over 30,000 km from the center).



Motion of the Solar System's barycenter relative to the Sun

To calculate the actual motion of the Sun, you would need to sum all the influences from all the planets, comets, asteroids, etc. of the Solar System (see n-body problem). If all the planets were aligned on the same side of the Sun, the combined center of mass would lie about 500,000 km above the Sun's surface.

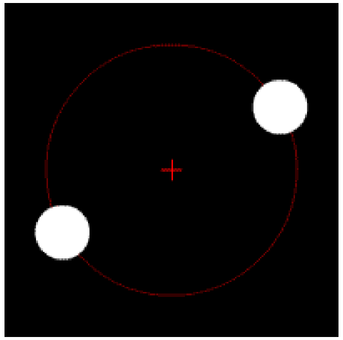
The calculations above are based on the mean distance between the bodies and yield the mean value r_1. But all celestial orbits are elliptical, and the distance between the bodies varies between the apses, depending on the eccentricity, e. Hence, the position of the barycenter varies too, and it is possible in some systems for the barycenter to be *sometimes inside and sometimes outside* the more massive body. This occurs where:

$$\frac{1}{1-e} > \frac{r_1}{R_1} > \frac{1}{1+e}$$

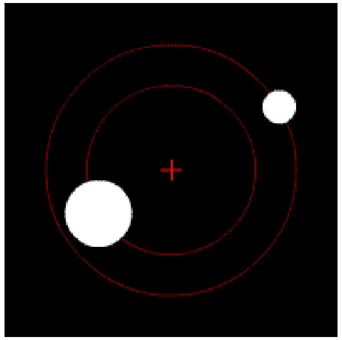
Note that the Sun–Jupiter system, with $e_{\text{Jupiter}} = 0.0484$, just fails to qualify: $1.05 < 1.07 > 0.954$.

Gallery

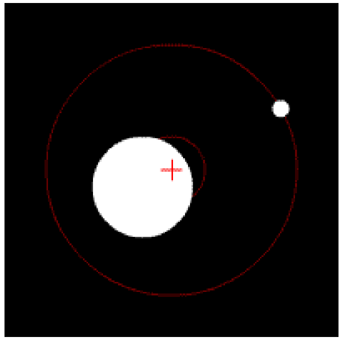
Images are representative (made by hand), not simulated.



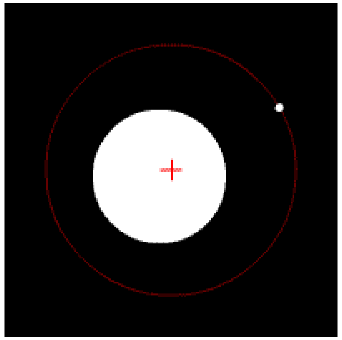
Two bodies with the same mass orbiting a common barycenter (similar to the 90 Antiope system)



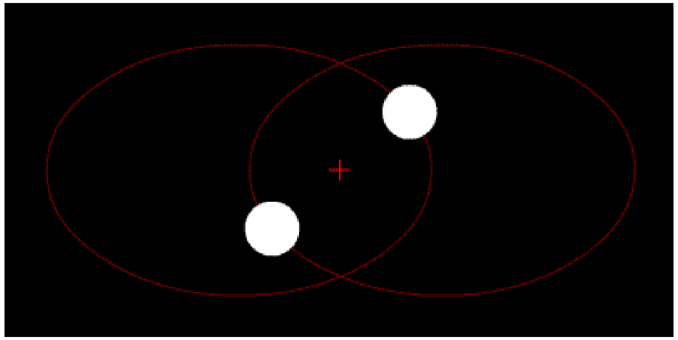
Two bodies with a difference in mass orbiting a common barycenter external to both bodies, as in the Pluto–Charon system



Two bodies with a major difference in mass orbiting a common barycenter internal to one body (similar to the Earth–Moon system)

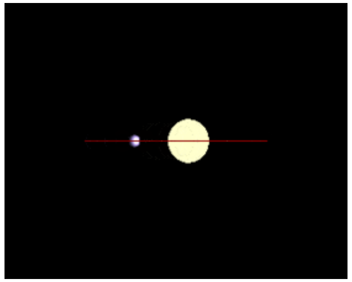


Two bodies with an extreme difference in mass orbiting a common barycenter internal to one body (similar to the Sun–Earth system)



Two bodies with the same mass orbiting a common barycenter, external to both bodies, with eccentric elliptic orbits (a common situation for binary stars)

Scale model of the Pluto system: Pluto and its five moons, including the location of the system's barycenter. Sizes, distances and apparent magnitude of the bodies are to scale.



Sideview of a star orbiting the barycenter of a planetary system. The radial-velocity method makes use of the star's wobble to detect extrasolar planets

Relativistic corrections

In classical mechanics, this definition simplifies calculations and introduces no known problems. In general relativity, problems arise because, while it is possible, within reasonable approximations, to define the barycenter, the associated coordinate system does not fully reflect the inequality of clock rates at different locations. Brumberg explains how to set up barycentric coordinates in general relativity.[5]

The coordinate systems involve a world-time, i.e. a global time coordinate that could be set up by telemetry. Individual clocks of similar construction will not agree with this standard, because they are subject to differing gravitational potentials or move at various velocities, so the world-time must be slaved to some ideal clock that is assumed to be very far from the whole self-gravitating system. This time standard is called Barycentric Coordinate Time, or TCB.

Selected barycentric orbital elements

Barycentric osculating orbital elements for some objects in the Solar System:[6]

Object	Semi-major axis (in AU)	Apoapsis (in AU)	Orbital period (in years)
C/2006 P1 (McNaught)	2,050	4,100	92,600
C/1996 B2 (Hyakutake)	1,700	3,410	70,000
C/2006 M4 (SWAN)	1,300	2,600	47,000
(308933) 2006 SQ_{372}	799	1,570	22,600
(87269) 2000 OO_{67}	549	1,078	12,800
90377 Sedna	506	937	11,400
2007 TG_{422}	501	967	11,200

For objects at such high eccentricity, the Sun's barycentric coordinates are more stable than heliocentric coordinates.[7]

See also

- Barycentric Dynamical Time
- Centers of gravity in non-uniform fields
- Center of mass
- Center of mass (relativistic)
- Lagrangian point
- Mass point geometry
- Roll center
- Weight distribution

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