

VELOCITY IN AN ELLIPTICAL ORBIT

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Reference: Carroll, Bradley W. & Ostlie, Dale A. (2007), *An Introduction to Modern Astrophysics*, 2nd Edition; Pearson Education - Chapter 2, Problem 2.3.

We did a sample calculation of the Sun-Jupiter system using Kepler's laws by approximating the orbits of the Sun and Jupiter about the centre of mass by circles. We can, however, derive equations for the radial and tangential velocity components for the correct case of elliptical orbits. We can start with the polar equation of an ellipse:

$$(0.1) \quad r = \frac{a(1 - e^2)}{1 + e \cos \theta}$$

The velocity of an object in polar coordinates is

$$(0.2) \quad \mathbf{v} = v_r \hat{\mathbf{r}} + v_\theta \hat{\boldsymbol{\theta}}$$

$$(0.3) \quad = \dot{r} \hat{\mathbf{r}} + r \dot{\theta} \hat{\boldsymbol{\theta}}$$

Differentiating 0.1 we get

$$(0.4) \quad \dot{r} = \frac{dr}{d\theta} \dot{\theta}$$

$$(0.5) \quad = \frac{ae(1 - e^2) \sin \theta}{(1 + e \cos \theta)^2} \dot{\theta}$$

In deriving Kepler's laws, we got an expression for the total angular momentum of the system:

$$(0.6) \quad L = \mu \sqrt{GMa(1 - e^2)}$$

In vector form, the angular momentum can be expressed in terms of the velocity of the centre of mass as

$$\begin{aligned}
 (0.7) \quad \mathbf{L} &= \mu \mathbf{r} \times \mathbf{v} \\
 (0.8) \quad &= \mu \mathbf{r} \times (\dot{r} \hat{\mathbf{r}} + r \dot{\theta} \hat{\boldsymbol{\theta}}) \\
 (0.9) \quad &= \mu r^2 \dot{\theta} \hat{\mathbf{z}}
 \end{aligned}$$

Therefore

$$(0.10) \quad \dot{\theta} = \frac{\sqrt{GMa(1-e^2)}}{r^2}$$

Substituting 0.1 into this, we get

$$(0.11) \quad \dot{\theta} = \frac{\sqrt{GMa(1-e^2)}(1+e \cos \theta)^2}{a^2(1-e^2)^2}$$

From Kepler's third law relating the period P of the orbit to the semimajor axis a :

$$(0.12) \quad P^2 = \frac{4\pi^2}{GM} a^3$$

we can eliminate GM to get

$$(0.13) \quad \dot{\theta} = \frac{\sqrt{4\pi^2 a^4 (1-e^2)} (1+e \cos \theta)^2}{a^2 (1-e^2)^2 P}$$

$$(0.14) \quad = \frac{2\pi (1+e \cos \theta)^2}{P (1-e^2)^{3/2}}$$

From this we can get the velocity components:

$$(0.15) \quad v_\theta = r\dot{\theta}$$

$$(0.16) \quad = \frac{a(1-e^2)}{1+e\cos\theta} \frac{2\pi(1+e\cos\theta)^2}{P(1-e^2)^{3/2}}$$

$$(0.17) \quad = \frac{2\pi a(1+e\cos\theta)}{P\sqrt{1-e^2}}$$

$$(0.18) \quad v_r = \frac{dr}{d\theta}\dot{\theta}$$

$$(0.19) \quad = \frac{ae(1-e^2)\sin\theta}{(1+e\cos\theta)^2} \frac{2\pi(1+e\cos\theta)^2}{P(1-e^2)^{3/2}}$$

$$(0.20) \quad = \frac{2\pi ae\sin\theta}{P\sqrt{1-e^2}}$$

The square magnitude of the velocity is then

$$(0.21) \quad v^2 = v_\theta^2 + v_r^2$$

$$(0.22) \quad = \frac{4\pi^2 a^2}{P^2(1-e^2)} (1 + 2e\cos\theta + e^2(\sin^2\theta + \cos^2\theta))$$

$$(0.23) \quad = \frac{4\pi^2 a^2 (1 + e^2 + 2e\cos\theta)}{P^2(1-e^2)}$$

From 0.12 we get

$$(0.24) \quad v^2 = \frac{GM(1+e^2+2e\cos\theta)}{a(1-e^2)}$$

From 0.1 we have

$$(0.25) \quad \frac{2}{r} - \frac{1}{a} = \frac{2(1+e\cos\theta)}{a(1-e^2)} - \frac{1}{a}$$

$$(0.26) \quad = \frac{2(1+e\cos\theta) - (1-e^2)}{a(1-e^2)}$$

$$(0.27) \quad = \frac{1+e^2+2e\cos\theta}{a(1-e^2)}$$

Therefore, comparing with 0.24 we get

$$(0.28) \quad v^2 = GM \left(\frac{2}{r} - \frac{1}{a} \right)$$

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