The Physics of Space Travel

Mike Bailey
mjb@cs.oregonstate.edu

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Why Are We Even Talking About This?

Space travel is (or could be, or should be) the basis for a variety of games and simulations. For example,

https://www.kerbalspaceprogram.com/
Kepler’s Three Laws

These are simplified laws of motion for *one* light object in orbit around *one* heavier object. These laws don't take into account having more planetary objects than just these two.

Don't try to fly to Mars on these equations alone! 😊

1. If a lighter object is moving near a much heavier object, then the lighter object’s path is a conic section, depending on the lighter object’s speed. That conic section can be an ellipse, a parabola, or a hyperbola.

2. The area swept by the lighter object per unit time is a constant.

3. For elliptical orbits, the period squared is proportional to the semimajor axis length cubed.
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- **Perigee** = point on the ellipse closest to the heavy object
- **Apogee** = point on the ellipse farthest from the heavy object

Heavier object at one focus of the ellipse
2. The area swept by the lighter object per unit time is a constant.

Perigee = point on the ellipse closest to the heavy object

Apogee = point on the ellipse farthest from the heavy object
3. For elliptical orbits, the period squared is proportional to the semimajor axis's length cubed.

\[ T^2 = \frac{4\pi^2 a^3}{GM} \]

\[ T = \sqrt{\frac{4\pi^2 a^3}{GM}} \]

float Period = sqrt( 4.*M_PI*M_PI*a*a*a / (G*M) );
Even with Kepler’s Laws, We Still Need the Physics

The quasi moon—named Kamo’oalewa, after a Hawaiian word for a moving celestial object—measures less than 50 m (164 ft.) across and orbits Earth in a corkscrew trajectory that ranges from 40 to 100 times the 384,000-km (239,000 mile) distance of our more familiar moon. Its odd flight path is caused by the competing gravitational pulls of Earth and the sun, which continually bend and torque the moonlet’s motions, preventing it from achieving a more conventional orbit.

At first glance, the moonlet seems like nothing more than an asteroid. But asteroids tend to reflect brightly in certain infrared frequencies, and Kamo’oalewa does not. To investigate that mystery, University of Arizona grad student Ben Sharkey turned to a monocular telescope he says could “squeeze every last ounce of photons out of that object.” But its infrared signature remained stubbornly off.

At last, the answer suggested itself. One of Sharkey’s advisers once published a paper on lunar samples collected by Apollo astronauts. When Sharkey compared his telescope data with that earlier research, the results matched perfectly—the odd rock was clearly once part of Earth’s main moon.

How did Kamo’oalewa shake free? The moon’s been getting bombarded by space rocks for billions of years, resulting in all manner of lunar debris getting ejected into space. Kamo’oalewa is one such piece of lunar rubble, but rather than simply tumbling off into the expanse, it found itself a quasi satellite in its own right.

Given its unstable orbit, the little moon won’t stick around for long. Sharkey and others estimate it will remain an earthy companion for only about 300 more years, after which it will break free of its current gravitational chains and twist off into the void. Originally a part of the moon, then a companion of Earth, it will spend the rest of its long life traveling on its own.
Newton’s Law of Gravitation

\[ F = \frac{G m_A m_B}{r^2} \]

\[ G = 6.673 \times 10^{-11} \text{ newtons} \cdot \text{meters}^2 \text{ kilograms}^{-2} \]

\[ W = mg \]
\[ g = \frac{G m_{\text{earth}}}{r^2} = 9.8 \text{ meters} \text{ seconds}^{-2} = 32.2 \text{ feet} \text{ seconds}^{-2} \]

Only on the surface of the Earth

Masses

\[ m_{\text{sun}} = 1.99 \times 10^{30} \text{ kilograms} \]
\[ m_{\text{earth}} = 5.97 \times 10^{24} \text{ kilograms} \]
\[ m_{\text{moon}} = 7.35 \times 10^{22} \text{ kilograms} \]
\[ m_{\text{mars}} = 6.39 \times 10^{23} \text{ kilograms} \]
void DistanceSquaredAndUnitVector( struct xyz *body, struct xyz *state, float *distSquared, struct xyz *unit )
{
    float dirx = body->x - state->x;
    float diry = body->y - state->y;
    float dirz = body->z - state->z;
    float lenSquared = dirx*dirx + diry*diry + dirz*dirz;
    float length = sqrt( lenSquared );

    *distSquared = lenSquared;
    unit->x = dirx / length;
    unit->y = diry / length;
    unit->z = dirz / length;
}

In

Out
Applying the Law of Gravitation to What We Already Know

struct xyz Pos[NUMBODIES];
float Mass[NUMBODIES];
struct xyz MyPos;
float MyMass;
struct state State;

void GetDerivs( struct state state, struct derivs *derivs )
{
    float sumfx, sumfy, sumfz;
    sumfx = sumfy = sumfz = 0.;
    for( int b = 0; b < NUMBODIES, b++ )
    {
        float distSquared;
        struct xyz unit;
        DistanceSquaredAndUnitVector( &Pos[b], &state, &distSquared, &unit );
        float force = G * Mass[b] * MyMass / distSquared;
        sumfx += force * unit.x;
        sumfy += force * unit.y;
        sumfz += force * unit.z
    }
    derivs->vx = state.vx;
    derivs->ax = sumfx / MyMass;
    derivs->vy = state.vy;
    derivs->ay = sumfy / MyMass;
    derivs->vz = state.vz;
    derivs->az = sumfz / MyMass;
}
Applying the Law of Gravitation to What We Already Know

```c
void AdvanceOneTimeStep()
{
    struct derivs Derivatives1, Derivatives2;
    struct state State2;

    GetDerivs( State, &Derivatives1);
    State2.t   = State.t   + Δt;
    State2.x   = State.x   + Derivatives1->vx * Δt;
    State2.y   = State.y   + Derivatives1->vy * Δt;
    State2.z   = State.z   + Derivatives1->vz * Δt;
    State2.vx = State.vx + Derivatives1->ax * Δt;
    State2.vy = State.vy + Derivatives1->ay * Δt;
    State2.vz = State.vz + Derivatives1->az * Δt;

    GetDerivs( State2, &Derivatives2 );
    float aavgx = ( Derivatives1->ax + Derivatives2->ax) / 2.;
    float aavgy = ( Derivatives1->ay + Derivatives2->ay) / 2.;
    float aavgz = ( Derivatives1->az + Derivatives2->az) / 2.;
    float vavgx = ( Derivatives1->vx + Derivatives2->vx) / 2.;
    float vavgy = ( Derivatives1->vy + Derivatives2->vy) / 2.;
    float vavgz = ( Derivatives1->vz + Derivatives2->vz) / 2.;
    State.x = State.x   + vavgx * Δt;
    State.y = State.y   + vavgy * Δt;
    State.z = State.z   + vavgz * Δt;
    State.vx = State.vx + aavgx * Δt;
    State.vy = State.vy + aavgy * Δt;
    State.vz = State.vz + aavgz * Δt;
    State.t   = State.t   + Δt;
}
```

Initialize();
AdvanceOneTimeStep();
Finish();
But, Just Because We Are Using X-Y-Z Equations, Doesn’t Mean We Can Travel in a Straight Line From One Place to the Next

Your travel path is still influenced by gravitational bodies in your vicinity, especially, in our case, the Sun in the center. When traveling within our solar system, you will always be in some sort of solar orbit.

NASA’s Mars Perseverance Rover Spacecraft Path:

https://mars.nasa.gov/mars2020/timeline/cruise/