HW5 EMA 550, University of Wisconsin, Madison

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problem 1

A spacecraft is initially in a 300 km altitude circular orbit about the Earth in the ecliptic plane. It is to be sent on a Hohmann transfer to Saturn, also in the ecliptic plane. Assume that Saturn is in the correct position in its orbit for a flyby to occur when the spacecraft gets there.

Part (a)

Find ΔV_1 for Hohmann transfer

define constants to use

```
Clear["Global`*"];
AU = 1.495978 * 10^8;
r_earth = 6378;
μ_sun = 1.327 * 10^11;
μ_earth = 3.986 * 10^5;
R_earth = 1.496 * 10^8;
R_earth_SOI = 9.24 * 10^5;
R_saturn = 9.537 AU;
```

Velocity of earth relative to the sun

$$V_{earth} = \sqrt{\frac{\mu_{sun}}{R_{earth}}}$$

```
29.7831
```

spacecraft altitude over earth

```
alt = 300;
```

$$r_{b0} = r_{earth} + alt$$

6678

Find Hohmann paramters for trip to Saturn

$$a = \frac{R_{earth} + R_{saturn}}{2}$$

7.88157×10^{8}

Find V_p the velocity are perigee

$$V_{perigee} = \sqrt{\mu_{sun}\left(\frac{2}{R_{earth}} - \frac{1}{a}\right)}$$

40.0711

Find V_∞ the excess velocity to escape from Earth

$$V_{out} = V_{perigee} - V_{earth}$$

10.2881

Find V_{b0} at earth

$$V_{b0} = \sqrt{2\left(\left(\frac{V_{out}^{2}}{2} - \frac{\mu_{earth}}{R_{earth_{SOI}}}\right) + \frac{\mu_{earth}}{r_{b0}}\right)}$$

14.9786

Find V_{sat} the spacecraft speed around eath

$$V_{sat} = \sqrt{\frac{\mu_{earth}}{r_{b0}}}$$

7.72584

find ΔV_1

```
delV1 = Vb0 - Vsat
```

$delV_1 = V_{b0} - V_{sat}$

```
7.25277
```

Part (b) Angle calculation at departure

Calculate the angle past the Earth’s dawn-dusk line where the ΔV should be applied.

find *e* the eccentricty for the escape hyperbola

$$e = \sqrt{1 + \frac{V_{out}^2 V_{b0}^2 r_{b0}^2}{\mu_{earth}^2}}$$

```
2.76865
```

$$\eta = \text{ArcCos}\left[-\frac{1}{e}\right];$$

$$\text{Row}\left[\left\{"\eta \text{ Degree } = ", \eta * \frac{180}{\pi}\right\}\right]$$

```
η Degree = 111.173
```

$$\theta = \text{Pi} - \eta;$$

$$\text{Row}\left[\left\{"\theta \text{ Degree } = ", \theta * \frac{180}{\pi}\right\}\right]$$

```
θ Degree = 68.8269
```

Part (c)

For how long is the spacecraft on the heliocentric Hohmann transfer between Earth and Saturn? (Note: you do not need to calculate the time within either planet’s sphere of influence, as that will be small relative to the Hohmann transfer time, but you are welcome to do so and compare those values for yourself.)

find time to fly, which is half the period

```
T = 2 π Sqrt[a^3/μsun];
Row[{"time to fly in years = ", (1/2) T/(60*60*24*365)}]
```

$$T = 2\pi\sqrt{\frac{a^3}{\mu_{sun}}};$$

```
time to fly in years = 6.051
```

Part (d)

After crossing into the sphere of influence of Saturn, the spacecraft is to be placed in a circular orbit about Saturn with an orbital radius of 150,000 km. Calculate the ΔV2 required to place the spacecraft on this orbit. When spacecraft reaches saturn is has speed relative to sun of

Paramters to use

$r_{b0} = 150000;$
$\mu_{saturn} = 37931187;$
$R_{saturn_{SOI}} = 3.47 * 10\text{^}7;$

Find $V_{apegree}$ of the Hohmann transfer

$$V_{apegee} = \sqrt{\mu_{sun}\left(\frac{2}{R_{saturn}} - \frac{1}{a}\right)}$$

```
4.20171
```

find saturn speed relative to sun

$$V_{saturn} = \sqrt{\frac{\mu_{sun}}{R_{saturn}}}$$

```
9.64422
```

Find V_{in} the speed by which spacecraft enters saturn SOI

$$V_{in} = V_{saturn} - V_{apegee}$$

```
5.4425
```

Use energy equation to solve for V_{b0} at Saturn

```
Vb0 = Sqrt[2 ((Vin^2/2 - μsaturn/RsaturnSOI) + μsaturn/rb0)]
```

$$V_{b0} = \sqrt{2\left(\left(\frac{V_{in}{}^{2}}{2} - \frac{\mu_{saturn}}{R_{saturn_{SOI}}}\right) + \frac{\mu_{saturn}}{r_{b0}}\right)}$$

```
23.0908
```

Since spacecrasft will end up in an orbit around saturn, find its parking speed

$$\left(V_{sat} = \sqrt{\frac{\mu_{saturn}}{r_{b0}}}\right) // N$$

```
15.902
```

find ΔV_2

$$delV_2 = V_{sat} - V_{b0}$$

```
-7.18874
```

Find total speed change needed

$$totalV = Abs[delV_1] + Abs[delV_2]$$

```
14.4415
```

Problem 2

A spacecraft on an interplanetary mission in the same plane as Jupiter’s orbit about the Sun enters Jupiter’s sphere of influence. The spacecraft has a speed of 10 km/s relative to the Sun at this point, which you can estimate as the Jupiter’s average orbital radius about the Sun. (See the Planetary Constants sheet in your notes for values.) Assume that Jupiter is in a circular orbit about the Sun.

Part (a)

The largest possible value for the impact parameter, b, that will still result in a hyperbolic orbit about Jupiter in the patched conic method is Jupiter’s SOI radius. Find that value on the Planetary Constants sheet in the course notes and enter it here for reference.

Paramters

```
ClearAll["Global`*"];
AU = 1.495978 * 10^8;
r_earth = 6378;
μ_sun = 1.327 * 10^11;
μ_earth = 3.986 * 10^5;
μ_jupitor = 126 686 534;
R_earth = 1.496 * 10^8;
R_earth_SOI = 9.24 * 10^5;
R_jupitor = 5.203 AU;
r_jupitor = 71 492;
jupitor_SOI = 4.83 * 10^7;
bmax = jupitor_SOI;
```

Part(b)

For parts (b) through (g), assume that, relative to the Sun, the spacecraft is moving in the same direction as Jupiter when it enters Jupiter’s SOI

What is the speed of the satellite relative to Jupiter when it enters Jupiter’s SOI?

```
Vin = 10;
```

find Jupitor speed relative to sun

$$V_{jupitor} = \sqrt{\frac{\mu_{sun}}{R_{jupitor}}}$$

```
13.0571
```

Find speed of spacecraft relative to Jupitor

```
VinRelative = V_jupitor - Vin
```

```
3.05708
```

Part(c)

What is the smallest possible value for the impact parameter b? This value of impact parameter will result in a burnout radius that just grazes the surface of Jupiter

```
eq = bmin VinRelative == r_jupiter Sqrt[μ_jupiter / r_jupiter];

bmin /. First@Solve[eq, bmin];
(bmin = %) // N
```

```
984436.
```

Part(d)

Select as your impact parameter the value halfway between b_{min} and b_{max}. Note that value here for reference and use it as your impact parameter for the rest of the problem

```
b = Mean[{bmin, bmax}]
```

2.46422×10^{7}

Part(e)

Given the impact parameter from part (d), calculate the turning angle of the spacecraft relative to Jupiter during the flyby.

```
eq1 = (rb0) (vb0) == (b) (VinRelative);
rb0 = (b) (VinRelative) / vb0
```

$$\frac{7.53331 \times 10^{7}}{vb0}$$

setup the energy equation at Jupiter

$$eq2 = \frac{vb0^2}{2} - \frac{\mu_{jupiter}}{rb0} == \frac{VinRelative^2}{2} - \frac{\mu_{jupiter}}{jupiter_{SOI}}$$

$$-1.68168\, vb0 + \frac{vb0^2}{2} == 2.04995$$

Solve for V_{b0}

```
sol = vb0 /. NSolve[eq2, vb0]
```

```
{-0.950417, 4.31379}
```

```
vb0 = First@Select[%, Positive]
```

```
4.31379
```

check the correspoding r_{b0}

```
rb0
```

1.74634×10^7

Find e at jupitor and find η and θ

$$e = \sqrt{1 + \frac{(\text{VinRelative})^2 (\text{vb0})^2 (\text{rb0})^2}{\mu_{\text{jupitor}}^2}}$$

```
2.07476
```

$$\eta = \text{ArcCos}\left[-\frac{1}{e}\right];$$

$$\text{Row}\left[\left\{\text{"}\eta \text{ Degree = ", } \eta * \frac{180}{\pi}\right\}\right]$$

η Degree = 118.815

$$\theta = 2\,\eta - \text{Pi};$$

$$\text{Row}\left[\left\{\text{"}\theta \text{ Degree = ", } \theta * \frac{180}{\pi}\right\}\right]$$

θ Degree = 57.63

Part(f)

What is the spacecraft's heliocentric speed following the flyby?

$$\text{vd} = \sqrt{V_{\text{jupitor}}^2 + \text{VinRelative}^2 - 2\, V_{\text{jupitor}}\, \text{VinRelative}\, \text{Cos}[\theta]}$$

```
11.7086
```

Part (g)

What is the spacecraft's heliocentric flight path angle following the flyby

```
γd = ArcSin[VinRelative Sin[θ] / vd];
Row["γd in degree ", γd 180 / Pi]
```

```
Row[γd in degree , 12.7398]
```

For the remaining parts, assume that, relative to the Sun, the spacecraft DOES NOT arrive at Jupiter's SOI moving in the same direction at Jupiter. The spacecraft still has a heliocentric speed of 10 km/s at the distance of Jupiter's orbit from the Sun. But now it has a heliocentric eccentricity of 0.5. (What was the heliocentric eccentricity when the spacecraft arrived in the same direction as Jupiter, assuming that point was aphelion?)

Part(h)

What is the spacecraft's heliocentric flight path angle when it arrives at Jupiter's SOI?

```
Clear[a];
e = 0.5;
eq = Vin == Sqrt[μsun (2 / Rjupiter - 1 / a)]
```

$$10 == 364280.\ \sqrt{2.56951\times10^{-9}-\frac{1}{a}}$$

```
a = a /. First@NSolve[eq, a]
```

5.50681×10^{8}

```
γ = ArcCos[Sqrt[a^2 (1 - e^2) / (Rjupiter (2 a - Rjupiter))]];
Row[{"angle is ", γ 180 / Pi, " degree"}]
```

```
angle is 17.9875 degree
```

Part(i)

What is the spacecraft's speed relative to Jupiter

```
VinRelative = Sqrt[V_jupiter^2 + Vin^2 - 2 V_jupiter Vin Cos[γ]]
```

$$VinRelative = \sqrt{V_{jupiter}{}^{2} + Vin^{2} - 2\, V_{jupiter}\, Vin\, Cos[\gamma]}$$

```
4.70206
```

part(j)

Using the same impact parameter as in part (d), calculate the turning angle of the spacecraft relative to Jupiter.

```
Clear[vb0];
eq1 = rb0 vb0 == b VinRelative;
rb0 = b VinRelative / vb0
```

$$rb0 = \frac{b\, VinRelative}{vb0}$$

$$\frac{1.15869 \times 10^{8}}{vb0}$$

setup the energy equation at Jupitor

```
Clear[vb0];
```

$$eq2 = \frac{vb0^{2}}{2} - \frac{\mu_{jupitor}}{rb0} == \frac{VinRelative^{2}}{2} - \frac{\mu_{jupitor}}{jupitor_{SOI}}$$

$$-1.09336\, vb0 + \frac{vb0^{2}}{2} == 8.43177$$

Solve for V_{b0}

```
sol = vb0 /. NSolve[eq2, vb0]
```

```
{-3.15623, 5.34294}
```

```
vb0 = First@Select[%, Positive]
```

```
5.34294
```

check the correspoding r_{b0}

```
rb0
```

$$2.16864 \times 10^{7}$$

Find e at jupitor and find η and θ

$$e = \sqrt{1 + \frac{(\text{VinRelative})^2\,(\text{vb0})^2\,(\text{rb0})^2}{\mu_{\text{jupitor}}^2}}$$

```
4.4153
```

$$\eta = \text{ArcCos}\left[-\frac{1}{e}\right];$$
$$\text{Row}\left[\left\{\text{"}\eta\text{ Degree = ", }\eta * \frac{180}{\pi}\right\}\right]$$

```
η Degree = 103.09
```

$$\theta = 2\,\eta - \text{Pi};$$
$$\text{Row}\left[\left\{\text{"}\theta\text{ Degree = ", }\theta * \frac{180}{\pi}\right\}\right]$$

```
θ Degree = 26.1805
```

Part(k)

Assuming that the spacecraft flies behind Jupiter, what is the spacecraft's heliocentric speed following the flyby?

V_{jupitor}

```
13.0571
```

```
VinRelative
```

```
4.70206
```

```
Vin
```

```
10
```

$$\beta = \text{ArcSin}\left[\frac{\text{Vin Sin}[\gamma]}{\text{VinRelative}}\right]$$

```
0.716508
```

```
vd = Sqrt[V_jupiter^2 + VinRelative^2 - 2 V_jupiter VinRelative Cos[β + θ]]
```

$$vd = \sqrt{V_{jupiter}^2 + VinRelative^2 - 2\, V_{jupiter}\, VinRelative\, \mathrm{Cos}[\beta + \theta]}$$

```
12.0449
```

Part(L)

Assuming that the spacecraft flies behind Jupiter, what is the spacecraft's heliocentric flight path angle following the flyby?

$$\gamma_d = \mathrm{ArcSin}\left[\frac{VinRelative\, \mathrm{Sin}[\beta + \theta]}{vd}\right];$$

```
Row["γd in degree ", γd 180/Pi]
```

```
Row[γd in degree , 21.0979]
```