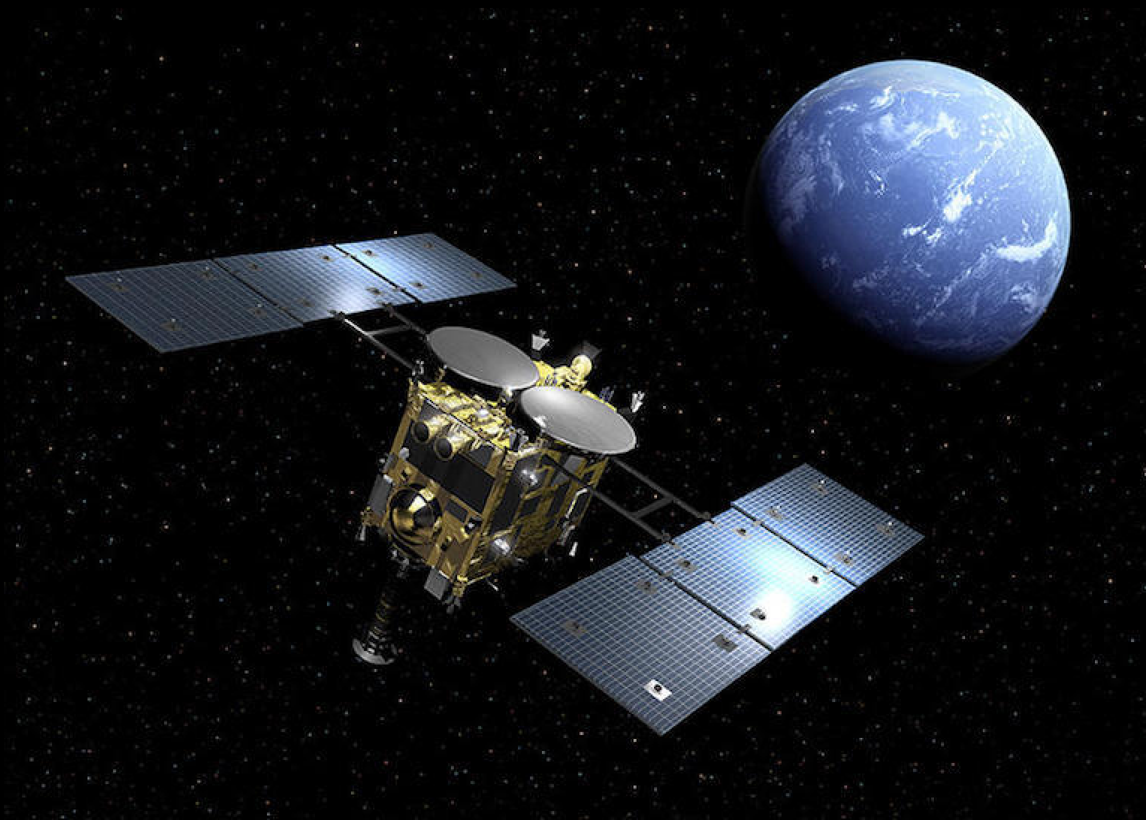


H-IIA 202, Hayabusa 2

Maddi Sanskar

190010041

Overview

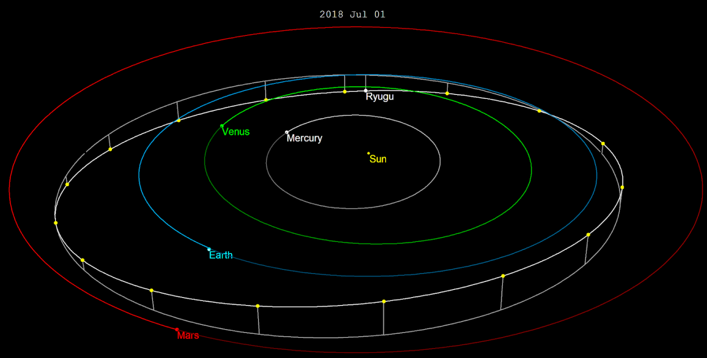
Hayabusa 2 is a Japanese mission launched in December 2014 on a six-year mission to study the asteroid 162173 Ryugu and to collect samples to bring to Earth for analysis.

- The Hayabusa 2 spacecraft arrived at the asteroid in June 2018.
- The spacecraft deployed two rovers and a small lander onto the surface.
- Hayabusa 2 fired an impactor into the asteroid in February 2019 to create an artificial crater. This allowed the spacecraft to collect a sample from beneath the surface of the asteroid.
- Hayabusa 2 delivered the asteroid sample to Earth on Dec. 6, 2020.
- The spacecraft is now on an extended mission to the small asteroid 1998 KY26.

About 162173 Ryugu

The asteroid's name means "dragon palace" in Japanese and refers to a magical underwater castle in a Japanese folktale. In the story, a fisherman visits the palace and returns with a mysterious box, much like the mysterious samples Hayabusa2 will be bringing back to Earth. The small asteroid's craters and rocks are all named for fairytales from around the world.

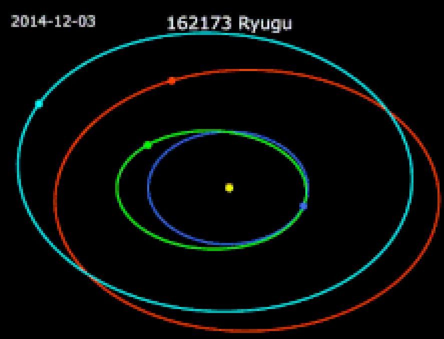
162173 Ryugu, provisional designation 1999 JU3, is a near-Earth object and a potentially hazardous asteroid of the Apollo group. It measures approximately 1 kilometre (0.62 mi) in diameter. It is a dark object of the rare spectral type Cb with qualities of a C-type asteroid.



Ryugu orbits the Sun at a distance of 0.96–1.41 AU once every 16 months (474 days; semi-major axis of 1.19 au). Its orbit has an eccentricity of 0.19 and an inclination of 6° with respect to the ecliptic. It has a minimum orbital intersection distance with Earth of 95,400 km (0.000638 au), equivalent to 0.23 lunar distances.

Orbital characteristics of 162173 Ryugu

Observation arc	30.32 yr (11,075 d)
Aphelion	1.4159 AU
Perihelion	0.9633 AU
Semi-major axis	1.1896 AU
Eccentricity	0.1902
Orbital period	1.30 yr (474 d)
Mean anomaly	3.9832°
Mean motion	0° 45^{m} 34.56^{s} / day
Inclination	5.8837°
Longitude of ascending node	251.62°
Argument of perihelion	211.43°

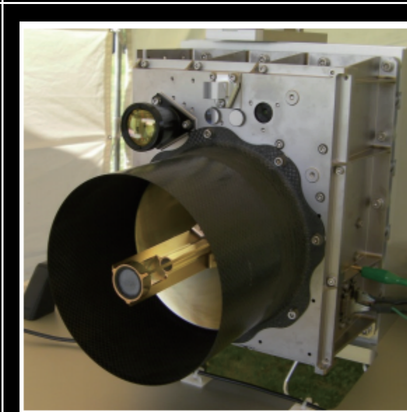
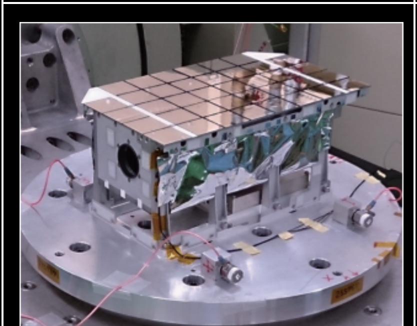
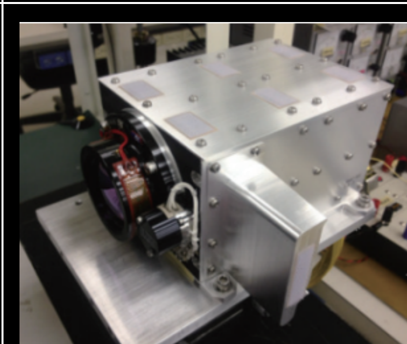
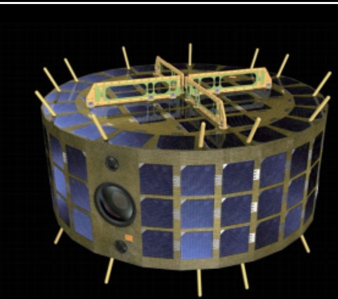


162173 Rygyu orbital trajectory.

Hayabusa 2 Primary Specifications

Mission type	Asteroid Rendezvous and Sample Return
Operator	JAXA
COSPAR ID	2014-076-A
SATCAT no.	40319
Mission duration	6 years, 5 months and 4 days elapsed
Spacecraft properties	
Launch mass	610 kg (1,340 lb)
Dry mass	490 kg (1,080 lb)
Dimensions	Spacecraft bus: 1 × 1.6 × 1.25 m
	Solar panel: 6 m × 4.23 m
Total thrust (ion drive)	28 mN
Specific impulse (Isp)	3000 seconds
Acceleration	49 μm/s2
Power	2.6 kW (at 1 au), 1.4 kW (at 1.4 au)
Start of mission	
Launch date	3 December 2014, 04:22:04 UTC
Rocket	H-IIA 202
Launch site	Tanegashima Space Center, LA-Y
Contractor	Mitsubishi Heavy Industries
End of mission	
Landing of Re-entry capsule	5 December 2020 at Woomera, Australia
Flyby of Earth	
Closest approach	3 December 2015
Distance	3,090 km (1,920 mi)
Rendezvous with (162173) Ryugu	
Arrival date	27 June 2018, 09:35 UTC
Departure date	12 November 2019
Sample mass	5.4 grams (including gas samples)
(162173) Ryugu lander 1 Landing date	21 February 2019
(162173) Ryugu lander 2 Landing date	11 July 2019
Flyby of Earth (Sample return)	
Closest approach	5 December 2020

Scientific Instruments:

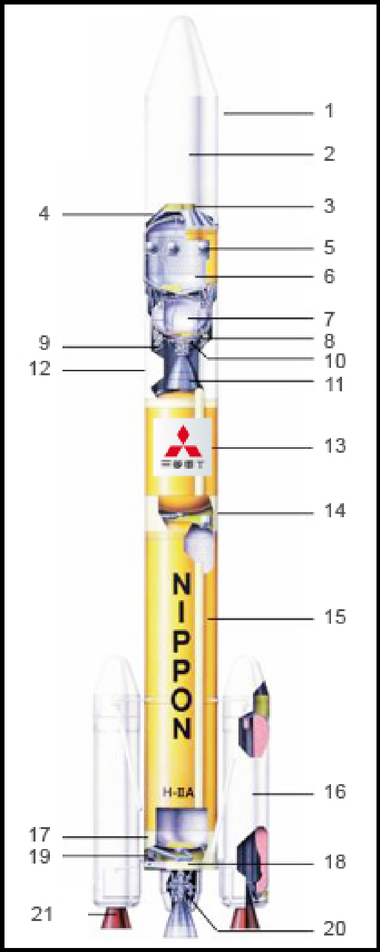
Optical Navigation Camera (ONC)	Laser altimeter (LIDAR)	Small lander (MASCOT)
		
Near-infrared spectrometer (NIRS3)	Thermal infrared spectrometer (TIR)	Small rovers (MINERVA-II-1 (A, B), 2)
		

H-IIA 202 Specifications

Manufacturer	Mitsubishi Heavy Industries
Height	53m
Diameter	4m
Launch Mass	285,000kg (without payload mass)
Stages	2
First Stage Engine	LE-7A×1
Second Stage Engine	LE-5B×1
Solid Rocket Booster	2

Orbit altitude	Payloads
Geosynchronous Transfer Orbit(GTO) about 36,000km	4,100kg
Low Earth Orbit(Inclination:30 degrees) about 300km	11,000kg
Sun Synchronous Orbit about 800km	3,600-4,400kg
Escape from the Earth Gravitation - Planetary Mission	2,500kg

H2A202 Launch Vehicle Configuration



1. Payload Fairing
2. Satellite (Spacecraft)
3. Payload Adapter
4. Payload Support Structure
5. Cryogenic Helium Gas Bottles
6. Second Stage Liquid Hydrogen Tank
7. Second Stage Liquid Oxygen Tank
8. Avionics Equipment Panel
9. RCS (Reaction Control System)
10. Ambient Helium Gas Bottles
11. Second Stage Engine (LE-5B Engine)
12. Interstage Section
13. First Stage Liquid Oxygen Tank
14. Center Body Section
15. First Stage Liquid Hydrogen Tank
16. Solid Rocket Boosters (SRB-A)
17. First Stage Engine Section
18. Auxiliary Engine
19. Ambient He bottles
20. First Stage Engine (LE-7A Engine)
21. SRB-A Movable Nozzle

Secondary payloads:

• Shin'en-2, a nanosatellite technology demonstration mission (17 kg) of Kyushu Institute of Technology and Kagoshima University, Japan. The objective is to establish communication technologies with a long range as far as the moon.

• ArtSat-2 (Art Satellite-2)/DESPATCH (Deep Space Amateur Troubadour's Challenge), a joint project of Tama Art University and Tokyo University. DESPATCH is a microsatellite of ~30 kg.

• PROCYON (PRoximate Object Close Flyby with Optical Navigation) is a microsatellite (67 kg) developed by the ISSL (Intelligent Space Systems Laboratory) of the University of Tokyo and JAXA.

Core Stage

Diameter	4m
Length	37.2m
Propellant	Liquid Hydrogen
Oxidizer	Liquid Oxygen
Launch Mass	114,000kg
Propellant Mass	102,800kg
LOX Mass	87,100kg
LH2 Mass	15,700kg
Total Thrust	1,078kN
Engine Length	3.4m
Engine Dry Weight	1,714kg
Burn Time	390sec
Specific Impulse	349s (SL) 446s (Vac)

Solid Rocket Boosters

Type	SRB-A	SRB-A3
Diameter	2.5m	2.5m
Length	15.1m	15.1m
Mass	76,400kg	76,600kg
Propellant	Solid	Solid
Propellant Mass	65,040kg	66,00kg
Thrust	2,260kN	2,305kN
Burn Time	108sec	115sec
Specific Impulse	280s	284s

Second Stage

Diameter	4m
Length	9.2m
Propellant	Liquid Hydrogen
Oxidizer	Liquid Oxygen
Launch Mass	20,000kg
Propellant Mass	16,600kg
LOX Mass	14,100kg
LH2 Mass	3,100kg
Total Thrust	137kN
Engine Diameter	2.49m
Engine Length	2.79m
Engine Dry Weight	269kg
Burn Time	530sec
Specific Impulse	447s

Payload Fairing

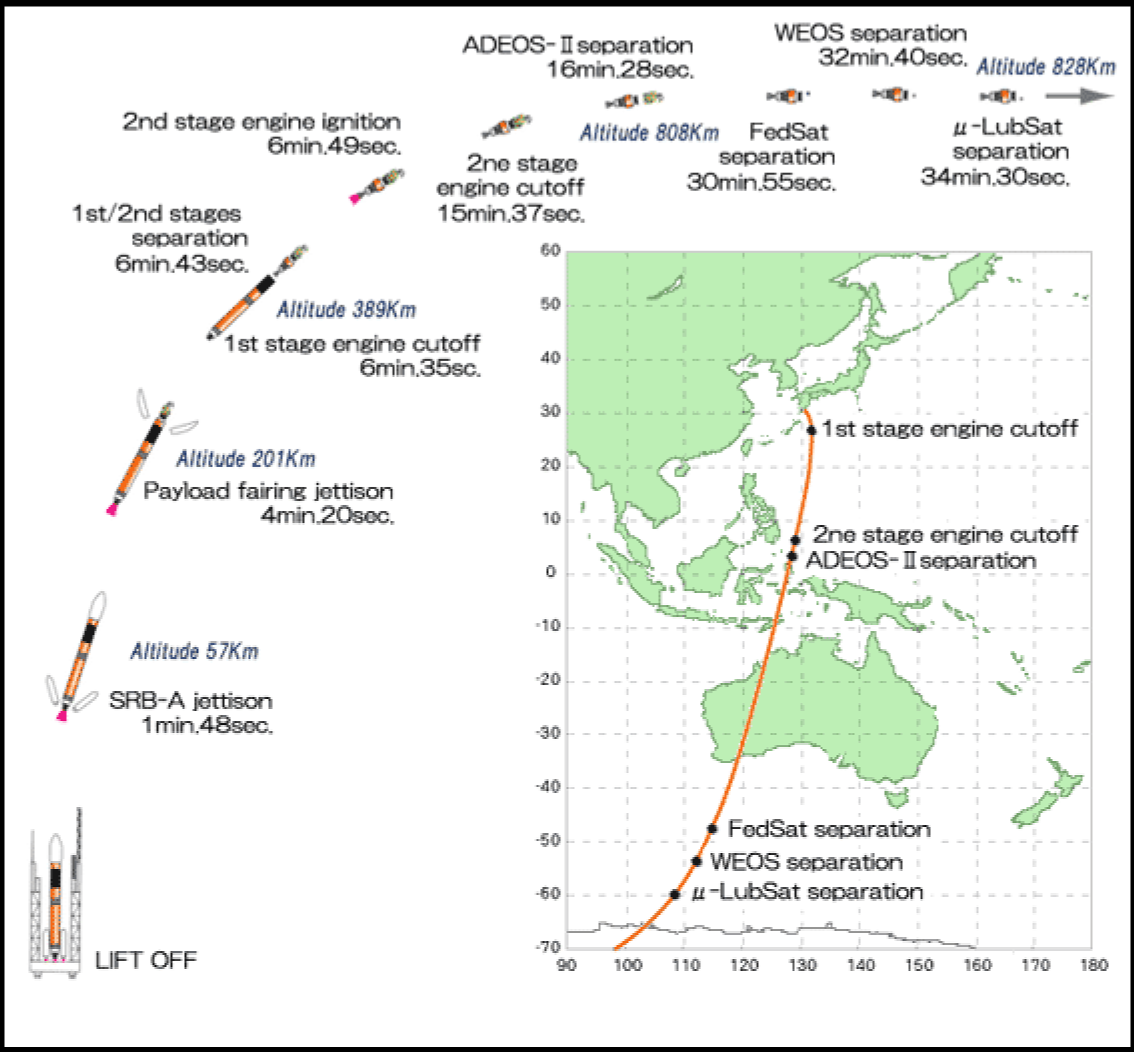
Length	4.07m
Diameter	12m
Mass	1,400kg

Hayabusa 2 mission ascent report

	First Stage	SRB-A	Second Stage	Payload
Length (m)	37.2	15.1	9.2	12
Diameter (m)	4	1	4	4.07
Mass (t)	114	151 (2 units)	20	1.4
Propellant mass	101.1	130 (2 units)	16.9	-
Thrust (KN)	1,098	5,040 (2 units)	137	-
Burning time(s)	390	108	530	-
Specific Impulse(s)	440	283	448	-

Take-off

Event	(Estimate quick review)
1. Liftoff	0 min. 0 sec.
2. SRB-A burnout	1 min. 33 sec.
3. SRB-A jettison	1 min. 47 sec.
4. Payload fairing jettison	4 min. 11 sec.
5. First stage main engine cutoff (MECO)	6 min. 36 sec.
6. 1st and 2nd stages separation	6 min. 44 sec.
7. Second stage engine lock-in (SELI1)	6 min. 54 sec.
8. Second stage engine cutoff (SECO1)	11 min. 20 sec.
9. Second stage engine lock-in (SELI2)	1 hour 39 min. 26 sec.
10. Second stage engine cutoff (SECO2)	1 hour 43 min. 31 sec.
11. Hayabusa2 separation	1 hour 47 min. 21 sec.
12. SHINEN2 separation	1 hour 54 min. 1 sec.
13. ARTSAT2-DESPATCH separation	1 hour 58 min. 11 sec.
14. PROCYON separation	2 hour 2 min. 21 sec.



ADEOS-Ⅱ separation
16min.28sec.
WEOS separation
32min.40sec.
Altitude 828Km
2nd stage engine ignition
6min.49sec.
Altitude 808Km
FedSat
separation
30min.55sec.
μ-LubSat
separation
34min.30sec.
2ne stage
engine cutoff
15min.37sec.
1st/2nd stages
separation
6min.43sec.
Altitude 389Km
1st stage engine cutoff
6min.35sc.
Altitude 201Km
Payload fairing jettison
4min.20sec.
Altitude 57Km
SRB-A jettison
1min.48sec.
LIFT OFF
1st stage engine cutoff
2ne stage engine cutoff
ADEOS-Ⅱ separation
FedSat separation
WEOS separation
μ-LubSat separation

Formulas for parallel staging

$Here,\ g = g_0 = 9.81 m/s^2$

$$h_b = \frac{m_0 g_0 I_{sp}}{\beta}[(1-\Lambda)\ln(1-\Lambda)+\Lambda] - \frac{1}{2}\tilde{g}\left(\Lambda\frac{m_0}{\beta}\right)^2 + V_0\Lambda\frac{m_0}{\beta} + h_0; \quad \Lambda = \frac{m_p}{m_0}$$

$$\epsilon_0 = \frac{\sum_{i=1}^{n} m_{s0-i}}{\sum_{i=1}^{n}\left(m_{s0-i} + m_{p0-i}\right)}; \quad \pi_0 = \frac{m_{01}}{m_0} = \frac{m_0 - \sum_{i=1}^{n}\left(m_{s0-i} + m_{p0-i}\right)}{m_0}$$

$$T_0 = \sum_{i=1}^{n} T_{0-i} = -g_0 \sum_{i=1}^{n} \dot{m}_{0-i} I_{sp0-i}; \quad \dot{m}_0 = \sum_{i=1}^{n} \dot{m}_{0-i}$$

$$T_0 = -g_0 \dot{m}_0 I_{sp0}; \quad I_{sp-0} = \frac{T_0}{g_0 \dot{m}_0} = \frac{\sum_{i=1}^{n} \dot{m}_{0-i} I_{sp0-i}}{\sum_{i=1}^{n} \dot{m}_{0-i}}$$

$$V_b = g_0 I_{sp} \ln\frac{m_0}{(m_0 - m_p)} - \tilde{g}\left(\frac{m_p}{\beta}\right)$$

Formulas for constant pitch rate solution

$$V(t) = \frac{\tilde{g}\sin\theta}{q_0}$$

$$\ln\frac{m_0}{m} = \frac{2\tilde{g}}{q_0 g_0 I_{sp}}(\sin\theta - \sin\theta_0)$$

$$t_b = \frac{(\theta_b - \theta_0)}{q_0}$$

$$\theta_b = \sin^{-1}\left\{\left(\frac{g_0 q_0 I_{sp}}{2\tilde{g}}\ln\frac{m_0}{m_b}\right) + \sin\theta_0\right\}$$

$$h(\theta) = \frac{\tilde{g}}{4q_0^2}(\cos 2\theta_0 - \cos 2\theta) + h_0$$

Formulas for constant T/m solution

$$V = k\frac{(\tan(\theta/2))^{n_0}}{\sin\theta} = k'\left[\tan^{n_0-1}\left(\theta/2\right) + \tan^{n_0+1}\left(\theta/2\right)\right]$$

$$k' = \frac{V_0}{\left[\left(\tan\left\{\theta_0/2\right\}\right)^{(n_0-1)} + \left(\tan\left\{\theta_0/2\right\}\right)^{(n_0+1)}\right]}$$

$$\Delta t = \frac{k'}{\tilde{g}}\left[\frac{\left(\tan\frac{\theta}{2}\right)^{\{n_0-1\}}}{\{n_0-1\}} + \frac{\left(\tan\frac{\theta}{2}\right)^{\{n_0+1\}}}{\{n_0+1\}}\right]_{\theta_0}^{\theta_b}$$

$$\frac{m_0}{m} = e^{\left(\frac{n_0\tilde{g}}{g_0 I_{sp}}\right)\Delta t}$$

$$h = \frac{k'^2}{2g}\left[\frac{\left(\tan\left\{\theta/2\right\}\right)^{2(n_0-1)}}{(n_0-1)} - \frac{\left(\tan\left\{\theta/2\right\}\right)^{2(n_0+2)}}{(n_0+2)}\right]_{\theta_0}^{\theta} + h_0$$

Ascent manoeuvres

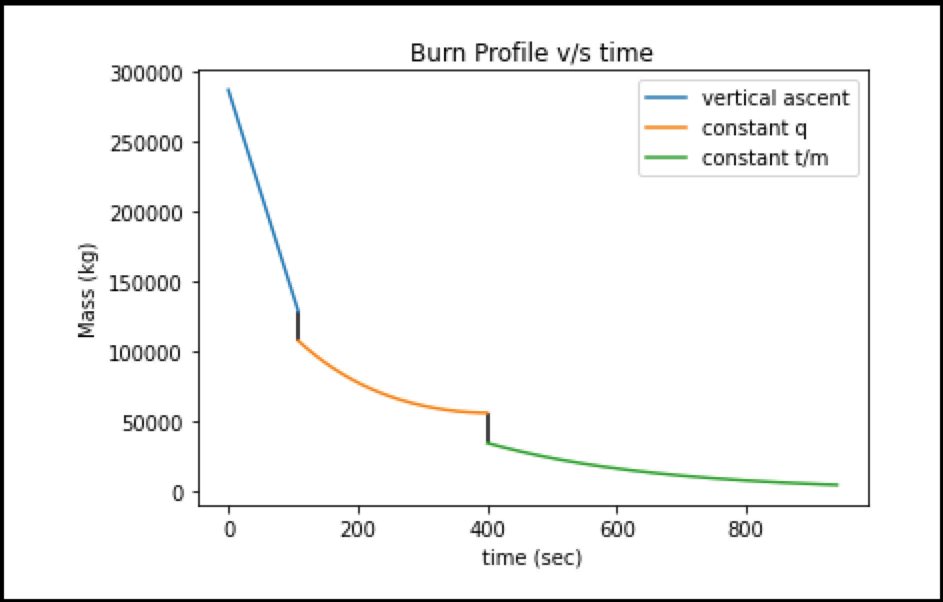
Action	Time(sec)	V_{final} (m/s)	M_{final} (T)	h_{final} (km)	θ_{final} (deg)
Vertical Ascent	0 - 108	1385.755883	128.43	57.367	0
Pitch Kick	108	1385.755883	128.43	57.367	29 From trial and error
Constant Pitch	108-400	4124.501828	55.863	439.6676	88.94640123
Constant T/m	400-940	6254.187346	4.5	821.613	90

Corresponding calculations are done in trajectory-ascent.xlsx (attached)

Pitch kick was found by trial and error using the Excel sheet, to minimise the errors and get close to the actual values

Burn Profile

The vertical ascent stage has a constant β of 1.463T/s (constant burn rate). After this, we observe a non-linear trend in the burn rates during gravity turn manoeuvres.



Burn profile plotted in burn_profile.ipynb (attached)

The black lines are booster inert mass jettison and core stage inert mass jettison.

```
[1] %matplotlib inline
    import matplotlib.pyplot as plt
    import matplotlib.gridspec as gridspec
    import numpy as np

    g0 = 9.81
```

```
[2] t1=np.linspace(0,108,500)
    t2=np.linspace(108,400,500)
    t3=np.linspace(400,940,500)

    mb1=286.4*1000-(258.974359+1203.703704)*t1
    beta1=np.ones(500)*(258.974359+1203.703704)
```

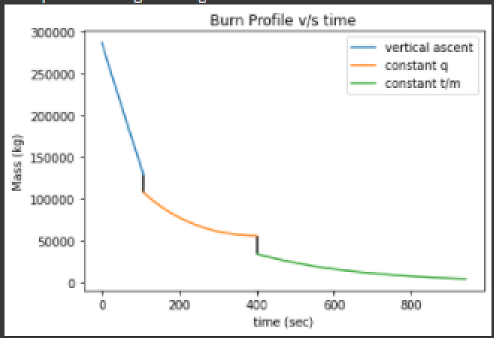
```
[3] def const_q(q0, thi, m0, t, Isp):
        th0 = np.deg2rad(thi)
        th = th0 + q0*t
        m = m0/np.exp(((2*g0)/(q0*g0*Isp))*(np.sin(th) - np.sin(th0)))
        return m
```

```
[4] def const_n(n0, m0,t , Isp):
        m = m0/np.exp((n0*g0*t)/(g0*Isp))
        return m
```

```
[5] mb2=const_q(0.003581272828,29,107.4307692*1000,t2-108,440)
    mb3=const_n(1.687449383,34.4*1000,t3-400,448)
```

```
[6] plt.plot(t1,mb1)
    plt.plot(t2,mb2)
    plt.plot(t3,mb3)
    plt.vlines(400,34.4*1000,55.86291029*1000)
    plt.vlines(108,107.4307692*1000,128.4307692*1000)
    plt.xlabel("time (sec)")
    plt.ylabel("Mass (kg)")
    plt.title("Burn Profile v/s time")
    plt.legend(['vertical ascent',"constant q",'constant t/m'])

    <matplotlib.legend.Legend at 0x7f80ff947c90>
```



Earth Orbital characteristics

Epoch J2000	
Aphelion	152100000 km (94500000 mi)
Perihelion	147095000 km (91401000 mi)
Semi-major axis	149598023 km (92955902 mi)
Eccentricity	0.0167086
Orbital period	365.256363004 (31558.1497635 ks)
Average orbital speed	29.78 km/s (107200 km/h; 66600 mph)
Mean anomaly	358.617°
Inclination	

7.155° to the Sun's equator; 1.57869° to invariable plane; 0.00005° to J2000 ecliptic

Longitude of ascending node	−11.26064°[5] to J2000 ecliptic
Time of perihelion	2021-Jan-02 13:59
Argument of perihelion	114.20783°

Orbital Manoeuvres

November 30, 2014: Launch

After launch, the Hayabusa2 will fly once around the Sun, similar to the Earth's. Then it will come back near the Earth in about one year to perform a swing-by.

End of 2015: Earth swing-by

After the swing-by, the Hayabusa2 will fly into an orbit similar to the 1999 JU3's. It will make about two rounds around the Sun to arrive at the 1999 JU3. The Hayabusa2 will explore the 1999 JU3 while the asteroid revolves once around the Sun.

Summer 2018: Arrival at the asteroid – Stay there for about 18 months.

Observing the asteroid using remote observation instruments, including the Near InfraRed Spectrometer (NIRS3) and the Thermal Infrared Imager (TIR).

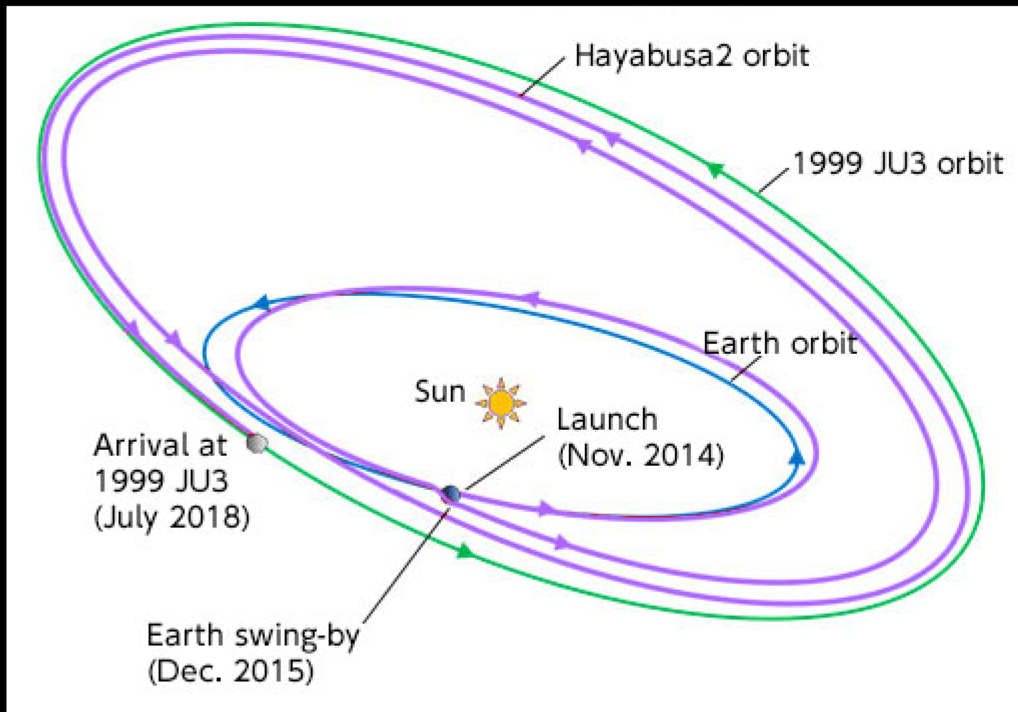
Separating the small rover "MINERVA" and small lander "MASCOT".

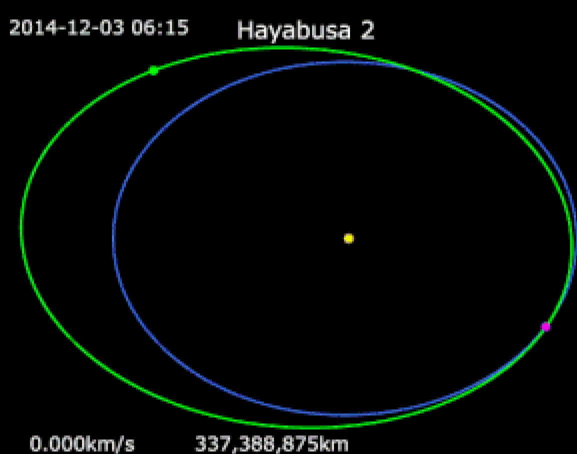
Capturing samples from the surface of the asteroid.

Separating the Small Carry-on Impactor (SCI) to make an artificial crater, touch down and acquire samples.

After leaving the 1999 JU3, the Hayabusa2 will fly around the Sun almost once and return to the Earth.

End of 2020: Return to the Earth





Animation of *Hayabusa2* orbit from 3 December 2014

Hayabusa2 162173 Ryugu Earth Sun

Departure solution

$$a_{TO} = \frac{R_{\oplus} + R_{\otimes}}{2}; \quad V_{perihelion} = \sqrt{\left(\frac{2\mu_{\odot}}{R} - \frac{\mu_{\odot}}{a_{TO}}\right)} \rightarrow v_{\infty} = V_{perihelion} - V_{\oplus}$$

$$\varepsilon_{dep} = \frac{1}{2}v_{dep}^2 - \frac{\mu_{\oplus}}{r_{dep}} = \frac{1}{2}v_{\infty}^2; \quad v_{dep} = \sqrt{v_{\infty}^2 + \frac{2\mu_{\oplus}}{r_0}}; \quad a_{hyperbola} = -\frac{\mu_{\oplus}}{2\varepsilon}$$

$$e = 1 - \frac{r_{dep}}{a_{hyperbola}}; \quad \text{For } \theta = \psi \text{ at } r = \infty \rightarrow \psi = \cos^{-1}\frac{-1}{e}$$

$\mu_{sun} = 1.327 * 10^{20}$

$\mu_{earth} = 3.986 * 10^{14}$

$$R = R_e + h_{final} = 821.63 + 6371 = 7192.63km$$

$$\Rightarrow \alpha_{TO} = a = 149598023km, \qquad V_{peri} = \sqrt{\left(\frac{2*1.327*10^{20}}{(147095+7.192)*10^6}\right) - \left(\frac{1.327*10^{20}}{149598023*10^3}\right)} = 30284.4m/s$$

$$V_{cir+} = \sqrt{\left(\frac{1.327*10^{20}}{149598023*10^3}\right)} = 29783.28m/s \quad \Rightarrow v_{\infty} = 501.12m/s$$

Flyby solution

$$v_{\infty i} = \sqrt{V_{Pl}^2 + V_i^2 - 2V_{Pl}V_i\cos\beta_i}; \quad \frac{v_{\infty i}}{\sin\beta_i} = \frac{V_i}{\sin(180^o - \zeta_i)}$$

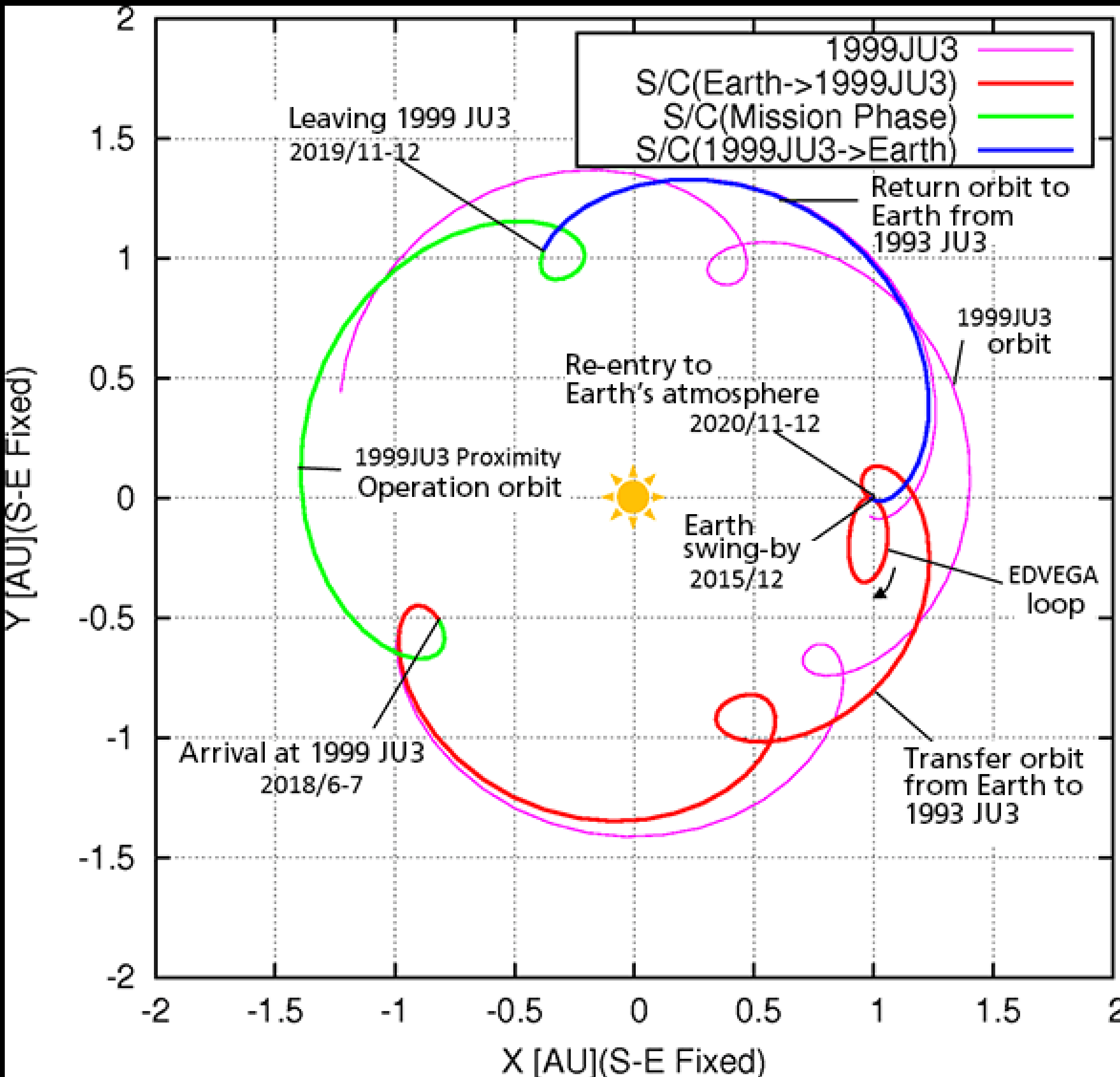
$$180^o - \zeta_i = \sin^{-1}\left(\frac{V_i \sin\beta_i}{v_{\infty i}}\right); \quad \text{If } \beta_i = 0^o \rightarrow \zeta_i = 180^o \text{ or } 0^o$$

Given, Vi=31.9 km/s

After a hyperbolic departure, Hayabusa 2 picks up the same orbit as the earth for nearly 1 earth revolution.

Then, we encounter a flyby, which pushes the satellite out of the earth's SOI.

After the flyby, Hayabusa 2 picks up an orbit similar to 162173 Ryugu, where it completes two revolutions until it reaches Rygyu for asteroid analysis.



1999JU3
S/C(Earth->1999JU3)
S/C(Mission Phase)
S/C(1999JU3->Earth)
Leaving 1999 JU3
2019/11-12
Return orbit to
Earth from
1993 JU3
1999JU3
orbit
Re-entry to
Earth's atmosphere
2020/11-12
1999JU3 Proximity
Operation orbit
Earth
swing-by
2015/12
EDVEGA
loop
Arrival at 1999 JU3
2018/6-7
Transfer orbit
from Earth to
1993 JU3
Y [AU](S-E Fixed)
X [AU](S-E Fixed)

References:

https://global.jaxa.jp/projects/rockets/h2a/

https://global.jaxa.jp/projects/sas/hayabusa2/

https://en.wikipedia.org/wiki/Hayabusa2

https://en.wikipedia.org/wiki/H-IIA

https://en.wikipedia.org/wiki/162173_Ryugu

http://www.astronautix.com/h/h-iia202.html

https://www.isas.jaxa.jp/visit/pdf/en/Hayabusa2_1_2.pdf

https://directory.eoportal.org/web/eoportal/satellite-missions/h/hayabusa-2#qlgSK186Herb

https://www.mhi.com/products/space/launch_srv_lineup.html

I consider this PDF as the bible for this assignment:
https://www.hayabusa2.jaxa.jp/en/enjoy/material/factsheet/FactSheet_en_v2.31s.pdf

https://en.wikipedia.org/wiki/Earth

An exciting summary video of the mission

https://drive.google.com/file/d/1gvhCMAjCq8imiYW5oYJz7Ej44MdNlwF0/view?usp=sharing

This mission was a grand success for JAXA and hence have sent Hayabusa 2 for another mission. We hope to see more from here.

https://global.jaxa.jp/press/2019/04/20190425a.html

Files attached

- Rygyu orbit.gif
- burn_profile.ipynb
- trajectory-ascent.xlsx
- Animation_of_Hayabusa2_orbit.gif
- Rygyu landing solarsystem.nasa.gov.gif

Thank you!!