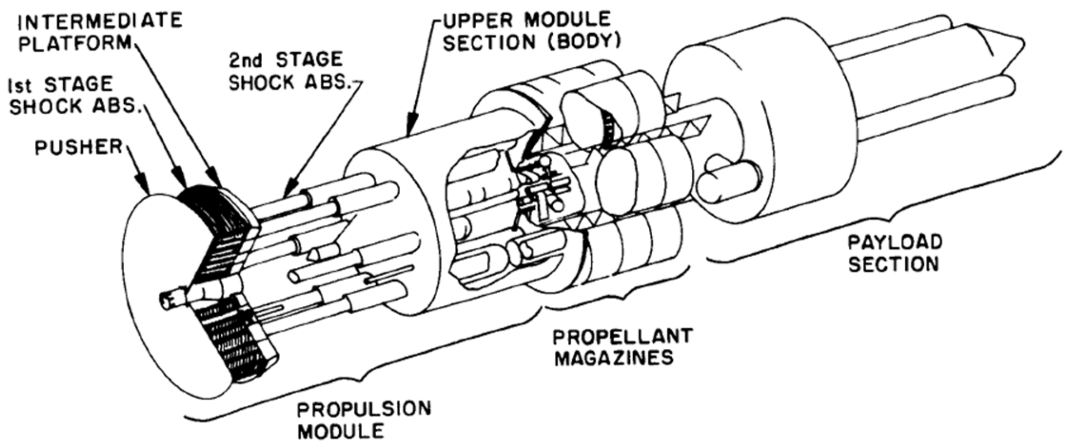
Exotic Matters

Squishy People and Hard Science

A scientific, mathematic TTRPG by
Alexander Lowry
Version: 0.1.1



Writing Team

Alexander Lowry Author

Lucas Sander Writer

Kate Sims Editor

Kitrick Fynaardt Mathemagician

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Playtesters

Kate Sims

Lucas Sander

Imagine you are standing in an elevator. As it begins to rise, you feel a momentary increase in weight. As it arrives at your floor, you feel a momentary decrease in weight as your body continues upward before being pressed once again into the floor by gravity. Then, the unthinkable happens. The cable snaps.

This elevator has none of the safety features standard in any modern elevator; it begins to plummet. As the elevator freely falls down the shaft, you begin to fall, too. Your stomach drops, your head swims. Your body was not built for this. The same earth pulling both you and the elevator accelerates you at equal rate, and your feet slowly leave the ground.

You are swimming in air, feeling a sensation you've only felt at small intervals and in terrible dreams that jolt you awake late at night. You feel no weight pulling you down. The floor recedes as quickly as you fall toward it; the effect is nothing seems to happen at all.

Of course, you expect to soon be flattened at the bottom of the shaft, but this unhappy doom never arrives. You are free to bounce around the elevator indefinitely. Your stomach drops, your head swims. Your body was not built for this. **This is what being in space is like.**

Imagine you are walking along a road.

Scale solar system stuff, speed of light/walking analogy.

This is the true scale of the solar system.

Imagine you are strapped into a chair of the space shuttle *Discovery* on Cape Canaveral, Florida on 1984 August 30. It is *Discovery's* first flight, mission STS-41-D to the International Space Station. You are on your back, looking up at blue Florida skies.

As the main engines ignite, a huge rumbling fills your body from head to toe, and the shuttle leans forward slightly. It balances back to vertical. The other astronauts call this the "twang" and it always happens as the asymmetrical rocket comes up to power on the launch pad. It is only held back by a handful of bolts. Moments later, the solid rocket motors ignite, charges destroy the bolts, and *Discovery* slips those surly bonds...

You are pressed back in your seat. You feel as if you weigh twice as much as normal. If the sound was loud before, it is truly immense now. You are shaken back and forth as *Discovery* begins its climb to the heavens. It took five seconds to pass 100 km/h and this is the slowest it will accelerate until it reaches orbit. The Florida coast falls beneath you. Soon, the clouds are falling behind too.

Discovery pitches over, and you are leaning back more and more. Forty-five seconds after leaping off the launch pad, *Discovery* is moving faster than sound. A continuous shockwave emanates in all directions, but the spacecraft leaves the booming sound behind. The sound of the engines can only travel to your ears through the structure of the craft itself.

The engines throttle back. The speed at which *Discovery* is moving means that the air pushes against the whole craft with immense pressure. The engines must reduce their push or else tear the whole ship apart.

But the air is already thinning. You travel faster, but the pressure is letting up. The shuttle throttles forward eagerly. You are now traveling 1,600 km/h. You are pressed back again.

Discovery first drops its boosters, which tumble away slowly. Blue skies give way to black void. Before long, she rolls half a turn, her belly facing Earth. The orange external tank falls away, too.

As the engines taper off into silence, you are released from the forces of acceleration. 350 kilometers below you is the mass of the Eurasian continent. You are higher in altitude than most humans have ever been. If the earth were an apple, you would be less than 3 milimeters from its skin. This is the farthest from its cradle humanity has ever made a permanent home. **Conclusion goes here.**

Your senses don't detect any motion, but that's far from the truth. You are traveling at 27,000 km/h.

You are a mere creature of flesh and bone, clinging to the side of a mote that weaves its way through a universe too vast and empty for your mind to ever understand. These exotic matters defy the meager senses you have been equipped with. But you are armed with a weapon that will digest these distances, speeds, and sizes to little symbols. You can flick yourself across the void with a pen. You are in possession of ***Mathematics***.

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Chapter 1

The Game

1 Introduction

Welcome to *Exotic Matters*! Exotic Matters is a Tabletop RPG (TTRPG) built around simple player stats and hard science. Live the golden age of science fiction, with real science, linear narratives, heroes solving problems with logic and diplomacy, and going on adventures enabled by technology.

This system is designed around somewhat realistic spaceflight, including patched-conics approximation of orbital mechanics. Characters, in contrast, have much more limited mechanics, relying instead upon roleplaying.

This book includes rules for play both in a single solar system where Faster-Than Light travel is still impossible, while the *Megastructures and Monoliths* module expands flight to interstellar distances while maintaining as much realism as possible. Exotic Matters (EM) is designed to be flexible and extensible, and the spaceship mechanics will work on their own with another system's character sheets and mechanics.

1.1 Overview

Players, with the guidance of the Game Master (GM), will take control of an interplanetary ship and soar madly through the vast empty spaces between planets. While many TTRPGs have each player creating and playing a single character, Exotic Matters has a game group populate a whole ship with crew and swap between different crew members as the game goes on. You may have two or three characters at your fingertips, or even share a character with another player!

The operation of the ship takes many hands after all, each member with different skills. Even in the far future, it's still rocket science. Players will use real-world physics to pilot their ship through the endless void of space. Charts and diagrams included in this book will help players calculate real-world physics easily and quickly.

The game takes the form of a conversation between players, as the story is told together. As the GM begins to tell the story, the players will move their characters through that story, responding to events, making choices, and exerting their meager will on a vast universe. Scene by scene, the story unfolds, and when players try to do something risky or dangerous, the dice resolve the moments of tension into success or failure. This keeps things a little fair - as it's impossible to determine all the factors[1] that go into the success or failure of making a risky or complex move[2], we flatten those many factors into a single die roll to randomly determine the outcome of that risk.

There is only one character stat in Exotic Matters, the **Gestalt Number**, and one die to go with it: the d12. Every roll is done on this stat though some rolls want to be over the target, while others want to be under. Checks involving skills

[1] Actually, this is untrue. Humans operate at the scale of classical mechanics meaning that even situations too complex for the human mind to predict are probably deterministic.

[2] For instance, even if you are a very good basketball player, throwing a three-pointer in basketball is affected by your focus, the positioning of your feet, the imperfections in the basketball, the imprecision of your muscles' movement, the sweat of your hands, etc.

of overt knowledge and rational thinking need to be equal or higher than the gestalt number to succeed, while checks involving intuitive sense and lived experience will need to roll equal or under the gestalt number. In addition, each character can gain **Skills**, which give them a bonus when doing a specialized task. Each character has only one stat, so a ship's roster full of varied specialties will ensure the crew can always get things done. Players may swap between player characters in the **Character Pool** at many points to pursue different goals.

These adventures are built scene-by-scene, the players acting out the drama and romance of a hard sci-fi story. The scenes string together to build the story over the course of the play session, and weekly play sessions can build each adventures into a sprawling space saga across the planets and through the stars. Lay back, buckle your seat restraint, and prepare for terminal count!

1.2 Play Requirements

Exotic Matters is best for 3–6 players, plus a GM. Each game session will probably take from one to four hours. Games can take as many sessions as your group wants to play. Some adventures are a one-shot, meaning they're over after the session. Some are episodic, stringing many smaller adventures together over several sessions, using the same crew. Other games are many-session, sweeping sagas that tell one story over the course of many sessions played over multiple months. For these, you will need someone organized to schedule sessions during everyone's busy lives.

While it is often the case in TTRPGs that the GM schedules game sessions, it can be good to take some cognitive load off the GM by appointing a player to run the schedule, or have players come together and propose a date to the GM. Since the ship is full of many crew members, not all of them are active on every mission, so the group does not need to require 100% attendance from players for each session.[3]

On page 10, a full list of required materials is enumerated, and additional optional materials are listed on page 11.

[3] Westmarches style works well for this system; see *Westmarches* in the *Running the Game* section

Required Materials:

These are required for play.

- This rulebook, for reference
- A twelve-sided die (d12), preferably one for each player (or digital d12 equivalent)
- A character sheet per playable character[4]
- Pencils or Pens[5]
- Printed (maybe laminated) copies of any nomograms you plan to use
- A ruler or straightedge for use on the nomograms

[4]These may change hands often — let the GM keep the originals between sessions so they're all in one place!

[5]Pressurized ballpoint pens are preferred in space, because pencils leave graphite dust in the air which may damage sensitive equipment.

Optional Supplements:

These are not required, but may provide useful reference or inspiration.

- Art books or history books about space travel
  - See *Reference, History, and Art Books* (page 114) for suggestions
- Extra paper and pencils for calculations
- High-density dehydrated snack foods, unlikely to create crumbs[6]
- A selection of a few devices and tables for calculating values, capable of:
  - Multiplication
  - Division
  - Exponents
  - Logarithms
  - Trigonometric functions

  such as:

  - A slide rule
  - A trigonometric table
  - A Curta Type-I handheld stepped-gear calculator
  - A spreadsheet application
  - A digital pocket calculator, like the **Casio fx-9750GIII**
  - Wolfram Alpha

Visicalc, **Lotus 1-2-3**, or **Excel**

[6] In null-G, crumbs float in all directions and get stuck in sensitive equipment.

2 Basics of Play

If you already know how to play Tabletop RPGs, you can probably skim until the *Calculations* section. If you don't, welcome! We hope this will be far from the last one you'll play. The game is a collaborative story told by the players with the help of the Game Master (GM). The players navigate characters through the universe that the GM creates.

This takes a little cooperation from everyone, so the following sections will outline how to establish a game and lay out rules, then to use the characters and universe you've created together to play the game.

2.1 Session 0

Before the game starts, the players and GM establish the foundations of the game. This is called **Session 0** because all this is done in the meeting before the game is actually played.

In Session 0, the group:

1. Establishes boundaries and the use of safety tools (page 27)
2. Creates a ship and determines its mission (page 31)
3. Creates a crew to serve aboard that ship (page 36)
4. Optionally, plays a few short scenes to get comfortable with the game and their new characters.

Before the first session, the GM also builds out the framework of the game universe (ships, planets, locations, and people) on their own, or with help from the players, and gives the players some background to let them integrate the crew with the story. The GM's plan can help characters find their backgrounds in the universe, and the GM should use the characters' stories to inform events and people in the wide universe. See the section *Running the Game* for a basic guide on GMing.

The GM acts as every person and environment that the player characters encounter, so they will have to plan out the planets, cities, ships, people, and aliens encountered by the player characters. They should arrive at each game session prepared for the next places the players may go during that session. In turn, the players should be clear about what they plan to do next session, to give the GM a fair chance to plan the story and expand the universe just one step ahead of players.

Ability to plan, but be flexible with those plans, is important. Having a stockpile of extra places and people ready will help tremendously when players go someplace unexpected. Hitting the edge of the planned universe can be awkward for everyone involved, so having just enough in terms of extra locations and people to make it to the end of the session will go a long way. See the section *Building the World* for a guide to preparing the world and people in it.

2.2 Sessions 1..N

As mentioned before, the game is a series of conversations the group has which build the story collaboratively. Like a movie, the story is broken down into scenes, where characters take actions to move the plot along and work toward their goals. Scenes have a beginning, middle, and end. In the beginning, the GM sets up the scene, describing the location, environment, and people present. Players respond and act in the middle. Once all player actions have been resolved, the scene wraps up and the GM describes the transition into the next scene.

Example of the conversation flow of a game:

> **Virgil (GM):** *Your ship,* The Stone's Throw, *is preparing for liftoff. What are each of you doing?*
> **Sayan (playing Calisto):** *I'm finishing the preflight checks on the bridge.*
> **Virgil:** *Great. Everything is checking out perfectly for launch. Dr. Grace, how about you?*
> **Josie (playing Dr. Grace):** *I walk onto the bridge.* (Now as Dr. Grace:) *"We've got a problem... the magistrate is refusing to give us clearance to launch."*
> **Jim (speaking as Roger):** *"I say we launch anyway. What's he going to do? Drag us back down?"*
> **Calisto (Sayan):** *"Well, this port is very important to us. We can't afford to lose favor here."*
> **Dr. Grace (Josie):** *"Calisto's right. We can't lose this stop on our route — there's too much at stake."*
> **Roger (Jim):** *"Alright, alright. Let's call him up and see what we can do."*
> **Josie:** *I get on the communications console and radio the office of the magistrate directly!*
> **Virgil:** *Alright. It's unusual to radio his office directly from a ship, but the signal is accepted by what seems to be his secretary.* (as secretary:) *"Excuse me, if you need to contact the dockmaster–"*
> **Dr. Grace (Josie):** *"What's the idea here?! We bring the year's supply of chocolate and you won't let us launch? Is this how you treat suppliers?"*

Then the scene continues to play out — perhaps Dr. Grace can reach the magistrate and quickly secure their permission. Perhaps she can't quite, and has to offer something in exchange. The GM's role is to play out this interaction in a believable manner, managing the several characters the players talk to in trying to get their ship to launch.

After the scene finishes, the group moves on to the next thing — either another scene, or some number-crunching. If our players above managed to get permission to launch, it's time for the number-crunching as they calculate the maneuver to get to orbit. If they didn't, it may be time for another scene where they decide to pay the magistrate a visit. That's the rhythm of the game: scene, scene, calculation, scene, calculation, scene, scene... until you run out of time in that session.

A note about scenes... Anyone can set up scenes. If the GM needs something to happen for the plot, they plan scenes with events for the players to interact with. If a player wants to try something, they can ask the GM to try something.

When reaching a crossroads in the story, the GM may also simply ask, "What would you like to do?" to the group, or "Does anyone have any scenes they'd like to run before we move on?" if there's downtime to let the players roam.

Example of offering to run scenes:

> **Virgil (GM):** *Your ship,* The Stone's Throw, *is launching for Phobos in six hours - that means you all have four hours of shore leave left. Does anyone want to run any scenes before we launch?*
> **Sayan (playing Calisto):** *Yeah, I think Calisto wants to tell her sister the truth about why she joined the space merchants.*
> **Virgil:** *Right, I remember Thebe felt pretty betrayed that you joined them, especially with the stranglehold they have on Mars.*
> **Sayan:** *Yeah, exactly. So I get on the train to her apartment.*
> **Virgil:** *Great. You get on the train to Arcadia City, and arrive after just a few minutes. You disembark and walk through the main square to Thebe's apartment block, and knock on the door. There's silence for a minute.*
> **Sayan:** *I knock again.*
> **Virgil:** *You finally hear a voice on the other side:* (Now as Phebe:) *"What now, Calisto? Haven't you said enough already?"*

If the GM forgets to offer a chance for players to take actions, players can ask directly.

Example of asking for a scene:

> **Virgil (GM):** *Your ship,* The Stone's Throw, *is launching to Phobos! The rocket engines ignite and you're pressed back into your seats–*
> **Sayan (playing Calisto):** *Can we hold on a second? There's a scene I'd like to run before we leave Mars.*
> **Virgil:** *Oh, of course. What do you want to do? You'd have had a few hours before being recalled to the ship.*
> **Sayan:** *Calisto wants to tell her sister the truth about why she joined the space merchants.*
> **Virgil:** *Fantastic. Ok, so you get on the train to Arcadia City...*

Then the scene plays out as normal before the GM resumes the next scene that was planned before. Of course, it isn't always possible to give a player a scene they want to have. Perhaps a player has had a lot of action and needs to bow out for a bit to let others in the limelight. Or perhaps something important is happening soon, and the players don't have time to do what they want.

In these cases, the GM should redirect the player, deferring the scene or offering an alternative. The GM can say "a few things are going to happen first — then we can get back to that" or "there's not quite enough time – you've got fifteen minutes, what can you do with that?" In any case, avoid a hard "no" when reasonable, instead taking a different path that tries to achieve the same goal. This alternative is often smaller or less ambitious, but is still an option the character might want to take.

Example of redirecting a player:

> **Sayan (playing Calisto:** *I want to talk to the captain of our sister ship,* The Loose Arrow, *to coordinate a plan in case we need backup.*
> **Virgil (GM):** *Unfortunately, you're passing behind horizon in a moment before you do your landing burn. You have about thirty seconds to send a coded message before you're out of radio sight.*
> **Sayan (as Calisto):** *Loose Arrow, be advised, we're dropping toward the Crashsite Crater with plans to board the ship. Plan to return in two hours, else call for help.*
> **Virgil:** *Perfect. You send off the message, unable to determine if* Loose Arrow *received your message, or was listening at all. You drop below the horizon and it falls off your long-range sensors.* Stone's Throw *ignites its engines, dropping its orbit...*

Avoiding Common Pitfalls

Here are a few things to keep in mind so that everyone can enjoy the game:

- The players don't play against each other, and definitely don't play against the GM. Everyone is on the same team!
- GM does not try to act as an enemy of the players — the GM wants them to succeed or fail fairly!
- The rules may have omissions or errors — the GM has the final ruling on resolving these.
- The GM may change, add, or ignore rules, as long as this is done consistently and fairly.
- Make sure you agree on lines, veils, and safety tools! It will save trouble later.

2.3 Risk, Uncertainty, and Dice

When players take actions in Exotic Matters, they start by simply narrating what they do. When the GM judges that an action is risky or has an uncertain outcome, they will tell the player to roll the die. The

GM will determine if this is a Tech roll, meaning the action involves using technology, navigating, piloting, and so on, or a Sense roll, meaning the action involves interpersonal relationships, diplomacy, talking, etc. Each player character has a single stat called the **Gestalt Number** that will determine how easy it is for them to succeed or fail at tech and sense rolls.

The player will roll a twelve-sided die (a.k.a. a *d12*). If they're rolling for a tech action, then they succeed if the dice roll is that player character's gestalt number or higher. But if they're rolling for a sense action, they succeed if they roll the player character's gestalt number or *lower*. So the more likely a given character is to succeed on tech rolls, the worse their ability to succeed on sense rolls, and vice-versa.

Player characters can also take skills, which allow them to get small bonusses on their roll, adding or subtracting with the dice roll to get them closer to their gestalt number. Skills are useful in specific situations and only apply to some rolls.

If an action will certainly succeed or fail, the GM will not ask the player to roll, they will just say the player does what they wanted, or found it too difficult to do. If the DM says that something is too difficult, they may offer the player a more realistic task or tactic that may still get them closer to that goal.

Once the die has been rolled, the GM will take that success or failure, and narrate what that means.

Example of die-rolling during play (including skills, which will be explained later)

Virgil (GM): *Stepping through the doorway into the dark of the pyramid, the engravings on the wall remind you of those found on the spolia and other fragments on TRAPPIST-1e.*

Sayan (playing Calisto): *I try to think back on what I studied there and see if I can read any of this.*

Virgil: *That's linguistics, so roll **Sense**. You'll want to roll lower than your gestalt number.*

Sayan: *Calisto's number is 8, so... okay, I've rolled a 9, which isn't enough, but I have mastery of the skill* linguistics *so my total is 7.*

Virgil: *For sure, many of the ideographs here are ones you saw on TRAPPIST-1e. You see some expressing danger, fear, death, and burial rites.*

Sayan (as Calisto): *"These must be warnings against grave robbers. Good thing it's been long enough what I'm doing can be considered archaology." I keep reading.*

Virgil: *You keep reading and your eyes glance across a sentence whose meaning is instantly clear: a standing figure, a crashing rock, and a lying figure. As you read this, you hear the stone of the entrance door grinding shut.*

Sayan: *Yikes! I better run. I'm trying to get through the door on time.*

Virgil: *Roll agility, that's **Sense** again.*

Sayan: *A 10! Rats! Even with my agility skill, that's 9, which is above my gestalt number of 8.*

Virgil: *The doors close with a boom right in front of your nose. Any closer and it would have taken off skin. You're in the dark.*
Sayan: *This thing has gotta be powered by* something. *I want to look for any motors or power sources. I get out a flashlight.*
Virgil: *Once you turn on your light, the situation is pretty obvious, so I'm not going to make you roll for it. You see a worn metal plate at the floor that's clearly machine-made.*
Sayan: *Okay, I'm going to scan it to see if I can figure out how it works.*
Virgil: *You get your scanner out, but it takes skill to interpret the readings. Roll electrician. This time it's* ***Tech****, meaning you want to roll higher than your gestalt number.*
Sayan: *Let's see. I rolled a 4. I have the electrician skill learned, but that's skill only a 5, which is well below my gestalt number.*
Virgil: *Unfortunately, it doesn't look like you can find out anything useful from these scans. Perhaps it's the dark, but you can't make heads or tails of the readings. You wish you had Chief Engineer Reynolds with you right now... but there still is the rest of the pyramid's interior.*
Sayan: *Alright, that means I've got to find another way out. I turn and head forward, eyes on the scanner for any more traps...*

2.4 Calculations

When a ship makes a maneuver, this must be calculated. There is no risk or dice roll involved with this calculation, and all player characters are assumed to be competent and trained enough to correctly make these calculations. The real challenge is for the players themselves.

The *Physics Foundations* section of this rulebook explains how these calculations are done in detail. The book provides several tools for simplifying the process of flight dynamics.

Calculations are specified with a number of *required known quantities* and *derived quantities*. These lists will tell you what you need to supply the equation, and what you will get out of it, respectively.

Function Signatures

Each calculation is also summarized by a **Signature**. The signature shows, at a glance, the required known quantities and derived quantities. It does not give any information about how the calculation is done. The purpose of a signature is to help you locate the correct equation quickly, and let you determine if the equation gets you the quantities you want as well as help you determine if you have the quantities you need.

For example, imagine a calculation called *Velocity*. This calculation requires the quantities Distance $\vec{d}$ and Time t. It then calculates Velocity $\vec{v}$. Therefore it will have the function signature:

$$Velocity(\vec{d}, t) \Rightarrow (\vec{v})$$

Likewise, consider a calculation

Integer Division or ID for short. This calculation requires the quantities Dividend d and Divisor v. It then calculates Quotient q and Remainder r. Therefore it will have the function signature:

$$ID(d, v) \Rightarrow (q, r)$$

A function can take in any number of arguments and produce any number of results.

3 History

3.1 First Escape: The Hermaians

Ever since the world narrowly avoided an energy crisis in the 1970s when the U.S. made a breakthrough in fusion power generation, humanity has slowly but surely turned from war and mass conflict to look outwards at the stars. The USSR recreated the U.S.'s attempts in 1976, and were the first to harness nuclear power to create rockets capable of breaking free of Earth's gravity well. Though the USSR did eventually collapse under the weight of its own bureaucracy, the world-renowned space program remained a point of pride for many Russians, and Yuri Gagarin was elected the first president of the new country on a platform of peaceful transition and investment in space expansion. Shuttle and Buran, rivals across countries, began to build stations by Earth; Saturn Nova and N-2 lifted modules to competing bases on Luna.

Never quite satisfied with American technology in the fusion systems they used, Gagarin was the one who directed the top minds in his space and energy programs to come up with an even greater energy source for the country. This was the beginning of the Hermes project that we know today. Gagarin proposed to the world that they build the Dyson Swarm.

But wait, I hear you saying, I know about the Hermians. They don't answer to anybody! Well, I'll remind you that humans had only barely pushed past the boundaries of that precious rock we evolved on. There were many things we did not yet know. Much preparation went into the station we now call The Mother before we were ready to send humans there. Getting materials there from Earth was essentially impossible, so the Russians negotiated a reluctant arrangement with the U.S. to build a port on Luna from which to launch to Mercury.

The Cosmonauts would prepare the equipment, and the Astronauts would build and maintain the mass driver to send it there. The push uphill to Luna was expensive, but the fuel savings from the railgun, too big to operate on-orbit, more than made up for it.

It was on one of the construction missions to Luna that it finally happened.

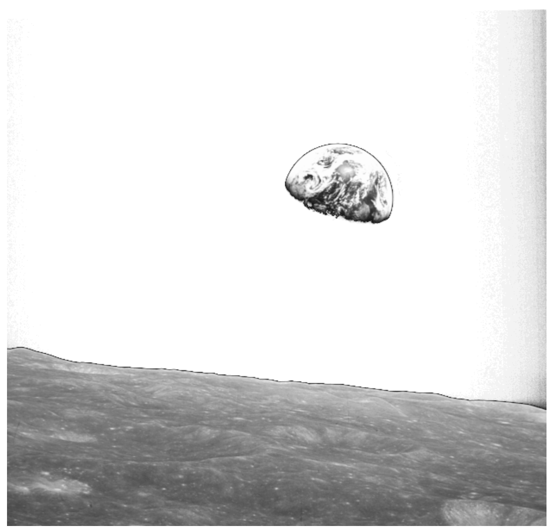


Figure 1.1: Earthrise from above Luna.

Have you heard of the Overview Effect, young one? I hope you get to feel it someday. You have yet to travel out there. This journey to Luna was the first in which a large group of laborers from both the U.S. and Russia traveled together to Luna. They did something their governments did not entirely anticipate, because it wasn't a scientific or, overtly, logistical factor in their mission. They became friends. It was inevitable, really. Life-changing experiences bond you with the people you have them with. But that friendship laid the foundation for a more profound change that the world was perhaps not ready for.

The Overview Effect describes what happens in our minds when we travel to space and see the entirety of our planet and understand the smallness of ourselves. For these first pioneers, they saw the planet on which every other person of their species made their home. The ultimate effect, almost universally, is one of empathy and connection with the rest of humanity. And this, young one, does not foster much loyalty to governments who do naught but enforce borders and hoard resources.

It is oft-repeated amongst Lunies that the Overview Effect happens twice on Luna: the first, seeing the blue pearl hanging on the neck of space and realizing what a fragile home human civilization has inhabited for at least 120 centuries recorded in the rocks. One realizes the true penalty for trespassing the Karman line: now, there is only a half-inch of insulation between life and death, rather than an ocean of nitrogen. Every space traveler expects this – groundhogs now think it cliche, though each one would become a convert if- but that's for another time.

The second occurs at first unconsciously: prowling, silent, latatent, then like a tubecat, appears, weighing down one's shoulders in an instant. One hears a weather report from Earth, quite incidentally, about some hurricane or tropical storm. This fact falls out of the conscious mind, and nests itself in the unconscious. Then, looking up, one notices the storm crawling across the ocean, a huge eye staring back. The Earth is not a painting. It is a living, breathing creature, whose breath passes through the lungs of all the things creeping along the ground.

It is possible to see the sky as a painted backdrop from Earth. The same is impossible from Luna. It is no wonder, then, that the astronauts and cosmonauts turned to each other before their own homelands when disaster occurred.

And disaster indeed occurred. It was June 2, 2004, just days after the arrival of the main crews that would operate the U.S. and Russian bases. The US base experienced a catastrophic loss of pressure. Thinking fast, astronauts replaced the escaping pressure long enough to evacuate the section and seal it off; when the tanks ran out, it collapsed, an impotent balloon.

Trapped in a chamberlock, the astronauts were ordered by NASA (the US agency of the time) to sit tight, to wait for rescue. NASA engineers worked tirelessly to mate a rescue lander with the most powerful rocket they had on hand, while NASA administrators tried desperately to convince the American president to accept help from Russia.

While ambassadors bickered, the cosmonauts got to work. Plainly seeing the astronauts needed help, they set their own mission control to the task of distracting the Russian government while they readied their rovers. Two rovers built for twelve each were meant as emergency shelters for two dozen cosmonauts, but could they carry the three dozen astronauts in addition to the rescue crew?

Packing emergency blankets, tarps, gaff tape, insulation tape, meteorite shield repair foam, and bottles of oxygen, they set off across the Lunar surface. They say you could see the huge plumes of parabolic dust thrown from Tycho crater in the wake of the speeding rovers from satellite pictures.

Arriving only hours later, the cosmonauts built improvised tunnels from the chamberlock to the pressurized Russian rovers in record time, carefully inflating their hastily-built tunnels and patching the smallest tears. They kept in radio contact, communicating through what English the cosmonauts knew – only one astronaut had any training in Russian. Once inflated, the cosmonauts on EVA watched cautiously as the astronauts shuffled into the first rover. Doors on both ends sealed, the cosmonauts deflated the tunnel, unstuck it, and pulled the next rover in place. More astronauts shuffled through.

It took three round trips between bases. Hot, humid, exhausted, and low on battery, the last rover and its passengers arrived at the Russian station.

The Russians opened their Christmas meal supply, hydrated it, and served a meal whose conversation mostly consisted of a pidgin where only words of Greek and Latin origin were enunciated with confidence.

Historians commented on the similarity with the 1914 Christmas Truce, and many feared that like that truce, the sides would once again become enemies once the euphoria of new camaraderie had subsided. But these brave people who were among the first to experience the Overview Effect as a collective, and they were also some of the top minds in their countries. It has never been confirmed, but there are strong suggestions inferred from following events that the astronauts and cosmonauts who first lived together in space made a pact with each other after that, one they kept for the rest of their lives: No Earthly governmental power would ever truly colonize space.

Whatever happened, those people were changed. The crews on the Luna stations were rotated out slowly to maintain a chain of experience, but what little record we have of non-governmental activity suggests that new crew members were quickly radicalized as well. For better or worse, there were also a small but outsized number of accidental deaths that hint at a desperation to keep a secret. Whatever that secret was, it grew into the shocking events of the Hermes 5 secession.

With some unrest planetside about the proliferating use of nuclear energy, and questions about the significant expansion of the space programs, the U.S. and Russia were pushing hard to expedite the Hermes program to demonstrate the invaluability of the effort. The first test satellites were launched to orbit around Mercury from the lunar port, and now it was time to send the operating station (the first iteration of The Mother) and its crew.

No one is sure how many of the following circumstances were due to chance and therefore taken advantage of, or due to the influence of the original Lunar community having spread further than we know; either way, several unusual facts shaped the Hermes 5 mission. Because of a quirk of launch scheduling and the rush to get to Mercury, the large crew making the journey inward in the system could not be replaced until (hours? days?) after they left, so Luna would be running on a skeleton crew. That replacement crew was also made up of a disproportionately large number of return visitors to Luna. (probably insert one or two other coincidental contributory facts when I dream them up)

Unbeknownst to ground control, there were several last-minute roster changes on the launch from Luna to Mercury. Most notably were the substitutions of two systems mechanics, Astrid Sayanov from Russia and Ven Boswell from the U.S., who were both supposed to remain moonside. A brief unsatisfactory explanation was given when ground control found out, but there was a scheduled communications blackout before they could ask anything more. When Hermes 5 came back online, the resupply mission to Luna was already out of Earth's sphere of influence, and both crews sent a message to Earth that the peoples and resources of space would no longer submit to Earthly powers, but would negotiate a new reality on their own terms and with their own leverage. Namely, all control of what would become the Hermian Dyson Swarm had already been mechanically vested in The Mother, so if Earth wanted to tap the power of their sun, they would have to do it through them.

There was, to say the least, an excess of tension in the days that followed. Empty threats of nuking Hermes 5, which the 'nauts knew would be a fruitless waste of money and precious knowledge; similarly empty speculations of aiming the energy from the Swarm at a strategic target on Earth; ultimately, the 'nauts would eventually need supplies from Earth, and Earth would very much like the cheap energy. And Mercury offered power to anyone willing to supply them.

A newly-formed political party, with roots in several nations, controversially used campaign funding to launch a power receiver satellite to low Earth orbit to get power from the Hermian swarm and beam it down to the ground. The party was disbanded and the leaders jailed for misuse of campaign funds, but the dam had been broken.

Other companies launched their own power relays as quickly as they could be built, receiving power and sponsoring supply launches to Mercury in exchange. The Hermians began shunting power to whoever sent them supplies, and trade of a pod with basic supplies for the massive quantities of energy that were returned was a no-brainer.

But There Ain't No Justice, and soon the biggest energy companies, who had made the initial investments, decided that a tenuous band of radicals did not deserve to distribute a planet's energy supply. They formed a coalition and tried to starve The Mother out to regain control. But the Hermians were never under the impression this operation would go off smoothly the first time – and they'd prepared. In addition to the crew swaps, an allied groundhog in payload integration had installed a primitive waste reclaimer instead of a redundant generator into one of the cargo rockets – along with the necessary nutrition mixture. Sayanov and Boswell placed a couple vials each of processor bacteria in their personal effects, so the bacteria would be safe in the radiation-shielded crew compartment. When the corps stopped shipping food, the Hermians didn't let anything on. They just smiled and said they were doing Just Fine.

Now, you may think the reprocessed bricks you tried were bland, but that's nothing compared to this primitive processor. Some said it was like eating charcoal briquettes. Some said you could still notice the lingering smell of the original waste – though, in the tight quarters of the first Mother, the smell of waste management lingered in every corner. Life was not pleasant and food was not good. But as long as they had energy, they had food, and as long as they had food they sat in communion just as they had for the first time on Luna more than ten years ago.

They outlasted the siege. An agreement was reached – the first of the many trade agreements that now exist in the solar system. A grateful populace enjoyed the power and Earth governments started shipping supplies for the public good. The investors lost their company, lost their monopoly, and moved onto other exploits. Though it is said they never left the public eye of ridicule, they never faced much consequence for the attempted starvation. They simply never worked in space again. There ain't no justice.

Sayanov and Boswell would continue to be instrumental in the early years of The Mother's operation, repairing and improvising parts of the station until they saw it as their own "Ship O' Theseus" or Shippo, for short. To all others who called it home, it was simply The Mother. Those two 'nauts were also responsible for holding it together in more ways than mechanically - it turned out that they were both members of and organizers with the IWW, resulting in a joke that became reality when an "S" was officially added to the name in 2019 (?) to make "Worlds" plural.

They had united an unlikely group of people in fighting to own the means of production, but for a long time they remained emphatic on one point: no other people were to come to Mercury. Their struggle to stay a cohesive unit with a singular radical dream had been a tenuous and even deadly one at times, and they did not trust that any new faces from Earth to not undermine that vision. Eventually, though, they acknowledged the need to accept a few more people into The Mother, and though they still don't let just anyone stay on the station, these days they are willing to trade more directly with people.

3.2 Venus

Any salesperson can put a shiny veneer on a shoddy product. It takes a special class of con to sell something for the very reasons it should be undesirable, and in 2060s, three people pulled off what many would call a dupe of planetary proportions - except it still hasn't ended.

The Orphan event had just begun to show its devastating effects on Earth, and though many highly populated areas were hardened to avoid the worst of the damage from planetary fragments, many remote, sprawling luxury areas were abandoned as too vulnerable. Economic concerns notwithstanding, many of the rich and uber-rich began to be frustrated at, quite frankly, the lack of opportunities to show off their wealth. Enter our heroes.

Benny Huff was a luxury travel agent who specialized in long-term accommodations - that is, he was in charge of planning month- to year-long vacations for the wives, mistresses, and families of corporate executives who made obscene amounts of money but had no time to spend it themselves. Huff witnessed the frustration of his clients firsthand, and was not too pleased himself with the corresponding decline in business. He was voicing his concerns at a dinner party one night and afterward a young person approached him, introducing themself as Bozz and hinting that they might have some interesting information for Huff. Bozz was obsessed with humanity's evolution to become a multi-planet species, and to that end had been paying close attention to space news and recent discoveries. This included a surprising amount besides the arrival and havoc of the Orphan, and they excitedly told Huff that the first experimental habitats had been proven to work on Venus. However, nobody saw a reason to capitalize on them - there was nothing to capitalize on. Yet.

After some further research, the two of them crafted a narrative based on some highly speculative reports that they were sure would appeal to Huff's clientele: Earth was becoming dangerous and, frankly, passe. A relative abundance of a viable energy source called deuterium had been found on Venus, they said, and was just waiting for quick-thinking investors to commit to starting operations there before the rest of the world took advantage. After playing up the opportunity for profit, they made a pivot. They made grand comparisons to the titans of industries past who lived and breathed their professions, reveling in the luxury it granted them. They showed plans of grand habitats loosely based on the successful experiments. Truly great men lived their dreams, they said. Bring your families, your whole communities, to build a home fit for a king, floating in the atmosphere above the mines that are making you rich.

It didn't work. For these billionaires, tossing a few million dollars at a startup venture on Earth was one thing, but staking half their fortune on an unproven, potentially deadly operation on an entirely different planet was quite another, and quite out of the question. Huff's pitches to his clients weren't always laughed at, but it wasn't an uncommon reaction. Bozz had a temper that often flared up when clients didn't understand technical parts of the pitch, and they began to grow more frustrated with Huff as well as his clients. Huff was commiserating about his lack of progress with his friend and associate Harada Yuki, a resort manager who had worked on various Pacific islands, after one of Huff's few successful terrestrial vacation bookings. Harada listened for awhile, shook his head, and told Huff exactly what he'd been doing wrong. "Each of these guys - and it will be guys that you get to go; not a whole lot of ladies give a shit about you or your magic planet. Each of these guys is a rich dick, Benny. It is important to keep that in mind, because up to this point, you've been appealing to the 'rich' part. How much money they'll make, how luxurious their lives can be, all that. Don't forget the 'dick' part, man. Specifically, the dick measuring contest. 'Course they don't want to go out there. Who in their right mind would? Well, if somebody in their right mind would, and has, and might get that claim to fame before they do… well, let's just say some of the blood rushes out of their brain and down to somewhere else."

Huff felt thunderstruck, and immediately worked with Hirada to create rumors of an unnamed, ultra-wealthy space enthusiast who planned to set up an exclusive operation on Venus. He then apologetically went back to the clients he had been talking to, and acknowledged that they had been right, it would be nearly impossible to get any of their own plans off the ground before this unknown figure did, and after that there really wouldn't be any point. Many rolled their eyes at his repeated mention of the idea, but a few stopped him and asked if he knew anything about the mysterious figure or his plans. And they were hooked.

It took much more planning, and a few fake launches and other purported activities by the shadowy space entrepreneur for proper motivation, but Huff, Bozz, and Hirada secured three major investors to begin building deuterium extraction operations on Venus - the plans to actually live there were much more tentative, but designs were certainly being drawn up. Though the investors could not be promised exclusivity to an entire planet, Huff assured each that theirs was the most valuable location and operation of the three. Several initial launches of equipment and infrastructure were made, and eventually workers themselves were sent to begin preliminary extractions. The investors (and, with much more anxiety, the three schemers) waited impatiently to hear of the first results.

They never did hear about those initial tests. In a series of events that can only be described as a dick-measuring contest gone too far, another billionaire had conspired with the crews of the original three to launch his own cargo rocket to orbit the planet and collect the deuterium product from all three operations without letting word get back to Earth until it was far too late. After this theft was discovered, war nearly broke out on Venus, and certainly a cannibalization of each other's operations did. Other foolish capitalists were drawn to the blood in the water and the rumor of a rich fuel source, and the resulting flood of rich amateur spacers nearly ruined Huff, Bozz, and Harada as they tried to assert their own privileges to Venus's promised wealth.

Ultimately, deuterium is fine as a backup source of energy, and some extraction operations on Venus continue to this day. But the luxury that the self-styled lords of industry there live in is a pretended one, trying to convince the outside world and perhaps themselves that their status and wealth are legitimate. The world writ large is not fooled, and the large number of workers and resident support staff are enticed only by massive wages. Soon after the uber-wealthy started building their homes there, the support staff formed a collective to assure their employers that even those paychecks would not cover the treatment and attitudes that the rich are used to on Earth. Given their utter dependence on those staff, the class power dynamic on Venus is something of an inverted one, though the staff amusedly allow their employers to pretend at an amount of power beyond what they could truly muster.

3.3 Mars

Some would argue that it is easier to build a spaceship than a space home. True, there were some engineering hurdles to the first, but we got over those and have gotten pretty good at the whole rocket thing. A rocket is, when you zoom out, a little prepackaged amount of space travel and exploration. You know how to launch it and, if there's a human on board, you (hopefully) know how and when to bring it back.

A space home, though, has to be somewhat self-sustaining, and that was the first problem that prospective Martians ran into.

The first few commercial missions to Mars were a mixed bag of failed ventures and small-scale safe bets, the latter of which mostly returned nickel-iron and other ores to be made into "Martian Steel," which was largely identical to

Earthen steel in all but name and novelty. While the novelty of an otherworldly tool, weapon, or other use of material sold well, it had to stretch quite a bit to justify the cost of shipping and handling. As other operations slowly made their attempts to put down roots, however, a different need arose.

The most successful of those initial ventures were those that made a thorough plan for water mining and refining. This issue often put less careful missions on the brink of failure, and forced them to either abandon the planet or relocate to one of the two established outposts in Arcadia, operated by the Honeywell conglomerate and Aurelia Enterprises.

These two companies made a nice additional profit by allowing other operators to tap into their superior water infrastructure, which was more than able to handle a few hundred more people. However, the population of Mars was quickly growing to more than a few hundred people.

Water shortages ensue, Honeywell/Aurelia get increasingly tyrannical, a popular uprising wrests water rights away from them and shuts down most commercial use of the precious resource so that a community can grow. Not sure what the jump to cities looks like, but perhaps a holistic approach that includes restrictive recycling to the point that they do on the ISS, water synthesis, and both strip and deep water mining.

4 Safety

Because tabletop RPGs are so free-form, it can be hard to predict what topics, themes, and events will crop up during play. With movies, shows, and video games, there are rating systems so that consumers can determine if a piece of media is appropriate for them. With TTRPGs, the story unfolds dynamically, and often in surprising ways, so different tools are needed to keep players comfortable and safe. We can't put a rating directly on the cover — the "rating" is going to vary by group. For this reason, it's important your individual group agrees upon which things are appropriate at the table, which can only happen implicitly, and which cannot happen at all.

Remember that mistakes can be common. Give grace and understanding to your fellow players without demanding they play exactly as you do. At the same time, frequent repeated mistakes and violations of agreed-upon rules should result in a serious conversation about respect at the table.

The following are a few (non-comprehensive) examples of safety tools and discussions for use at the table.

4.1 Lines and Veils

Lines and Veils are tools to help your group enumerate which topics should be avoided during the game. Establishing these lists beforehand can help the game run smoothly because it helps the group establish boundaries early-on, and avoid them before they become a problem.

Lines are topics that will not come up at all during play; as in, *"this line will not be crossed at all"*. For example, a common Line is torture. When something is a Line, players cannot do it to NPCs, NPCs cannot do it to other NPCs, and player characters certainly don't do it to each other.

Veils are topics which are implicitly allowed but not explicitly played. They are just as real as Lines, but represent a fast-forward, or "fade to black" moment in the game. For instance, if torture is a Veil instead of a Line, it may happen "off screen", its results immediately resolved in the next scene.

If one person has a Line or Veil, that Line or Veil is respected for the whole group; nobody should bring it up. Likewise, if something is a Line for one person but merely a Veil for someone else, that topic still becomes a Line for the whole group.

Some groups may be comfortable openly stating their Lines and Veils to each other. Other groups may want to privately submit their Lines and Veils to the Game Master, who will then compile the whole list and share it with the group, anonymizing the results.

With these lists in place, mistakes can be made, even by experienced players and GMs. Not all boundaries might be remembered at first. If a Line or Veil is crossed, players are encouraged to bring it up immediately.

It may also be useful to have a tool that can be used during play that allows instant feedback concerning these boundaries to help the game run smoothly. In the next section, one such tool will be explained.

4.2 The X-Card

John Stavropoulos' **X-Card** is recommended for use in this game and any other TTRPG. A summary will be provided here, but a full discussion with frequent updates is available at tinyurl.com/x-card-rpg.

The X-Card is simply an index card with an X written on it, often one for each player. The card becomes a tool to allow the deletion and retconning of any uncomfortable topic or event from the narrative of play by any player, at any time, for any reason. The topic or event can be one previously stated as a line or veil introduced by mistake, or a previously-undiscussed issue that a player (including the GM!) suddenly finds to be uncomfortable for play. It is especially helpful for groups of strangers or new groups who are still negotiating their styles of play.

The X-Card is designed to allow an easy and quick exit strategy that minimizes peer pressure. An understanding group will not question or interrogate an X-Card use. Even the presence of the X-Card will remind everyone at the table of their mutual responsibility for the safety of the whole group.

It may be easiest to introduce the X-Card with the text given by Stavropoulos for Game Masters to use with their players:

"I'd like your help – your help to make this game fun for everyone. If anything in this game makes anyone uncomfortable, just lift up this card up, or simply tap it. You don't have to explain why. When we lift or tap this card, we simply edit out anything X-Carded. And if there is ever an issue, anyone can call for a break and we can talk privately. I know it sounds funny but it will help us play amazing games together, and usually I'm the one who uses the X-Card to help take care of myself.

"Does everyone consent to the X-Card? Or is there a tool you would rather use? Either way, the people playing here are more important than the game we're playing. Thank you for helping up make this game fun for everyone!"

If the X-Card is used, the user need not explain; the scene will simply backtrack a few seconds and take a different route. It may be helpful or proactive for the user to be as specific as necessary to help the group steer around the topic in the future, though this is optional. No justification need be given, in reasons for using the X-Card, specific emotions, memories, nor circumstances that led the user to feel that way. Other players may quickly intuit what has gone wrong, but they may not; use mutual grace and discernment to attempt to avoid making the same mistake in the future.

Using the X-Card is not necessarily a failure on anyone's part. Likewise, the group is not automatically unsafe if it is never used. Repeated use should be cause for discussion, though, as the group renegotiates its expectations, and these conversations might need to be private with the GM or other players as appropriate. The X-Card does not replace all other tools nor absolve everyone of responsibility if it happens to not be used in the moment; is simply one of several tools that participants can agree on to heighten safety awareness at the table and facilitate difficult conversations.

4.3 Disability

There are two arenas in which the GM and players must consider disability:

within the fiction, and at the table.

In-Game

There are no explicit disability mechanics in Exotic Matters. In the future, many disabilities may be "cured" or rendered irrelevant by accessibility standards and technology. However, not all disabled people consider themselves in need of a cure. For instance, in the contemporary Deaf community, many people who may gain some amount of hearing through cochlear implants have chosen to not have them implanted. Their quality of life does not suffer from Deafness as they have friends and family outside the community who learn the local sign language, as well as other Deaf friends. It is only an inaccessible world that does not provide necessary resources.

Likewise, Autistic advocates argue that there is no need to "cure" Autism, because it is simply a neurodiversity. Disability in their view comes from a society that is not accessible. Others view certain symptoms of Autism as problems that medical advances or accessibility aids could alleviate – for instance, noise-canceling headphones to alleviate overstimulation and agoraphobia, or certain experimental medications to reduce sensory sensitivity.

In applying these to the table, *TODO: direct applications*

Don't do stories *about* disabilities you don't have. *TODO: explain how to include disability*

At the Table

It is important to make sure your table is accessible for all potential players. The game should be modified to include anyone who wishes to play.

TODO: More here.

This game in particular may be difficult for those who have dyscalculia – a learning disorder analogous to dyslexia that affects the ability to arrange and evaluate mathematical information. While it may be difficult to modify this math-centric game to include these players, the game comes with several charts and tools to minimize on-paper calculations. Beyond that, if your group contains someone who cannot do the math, make sure this person knows their contributions to the game are still important, or consider playing another game with that particular group.

4.4 Player-Player Conflict

Decide before the game starts how player-player conflict will be part of your game. Disagreements and discussion will inevitably part of the game, and drama is borne of conflict, but decide how intense these conflicts will get.

Star Trek famously preferred minimal conflict between the crew members of the Enterprise, instead facing external conflicts. Of course, many episodes still centered around discussions between Captain Kirk, Spock, and Dr. McCoy. The three had different perspectives and motivations which drove the plot forward. The conflict about how to resolve the episode's problem was the center of how the show was written, but the way these conflicts occurred was meant to be a professional, level-headed analysis of the problem even when strong emotions were involved.

Agree, as a group, about the types of conflict your crew will have. Will they get into fistfights? Hopefully astronauts are more mature than that!

Players can also talk out-of-character during a situation and agree to escalate the conflict, or let characters say and do hurtful things to each other. This can allow more heightened drama, because the "actors" of the scene are in agreement while their characters are arguing. Everyone can be sure they're heightening the drama without worrying about actually hurting each other's feelings.

4.5 Warmup and Cooldown

Your group will find it helpful to have a warmup and cooldown period. This can be as simple as small talk before and after the session, or some other ritual like Roses and Thorns.

Many TTRPG groups like to order out to eat while everyone gets settled in. This time is a good time for reviewing the previous session and getting caught up on what happened last time. Make sure the GM isn't the only one organizing food and discussion, because running the game itself is already a significant amount of work – share the work.

Roses and Thorns

After each game session, it may be helpful for players to talk about what they liked and didn't like about that session. The feedback can be split into two types: **roses** for moments and interactions that were surprising and delightful, and **thorns** for ones that were painful, annoying, or otherwise undesirable. These aren't personal criticism, but a way for the group to share and bond over things that were cool, or things that they'd like to avoid in the future.

5 Ship Creation

Before you create a crew, you need a ship. Your ship will serve as your home-away-from-home, and the way the ship is run will have a large effect on the type of adventures you have. In Exotic Matters , story comes before mechanics (as you'll also see in Character Creation). First, you'll tell the story of your ship, then you'll fashion its technical aspects to fit that story.

In the real world, Apollo needed to last a couple weeks and fall from the moon, so its design reflected that; it had a thick heat shield but only enough consumables to last those handful of days. The STS (Space Shuttle) needed to transport up to seven crew and lift heavy space station modules and telescopes, while making dozens of flights in its lifetime. Likewise, it was built with a large crew deck, a cargo bay big enough for a school bus, and large wings to help it land intact. Orion needed to last many weeks with or without crew in distant orbit from the moon, outside the protective magnetosphere, vulnerable to solar radiation, so it was given stronger radiation shielding than the shuttle. Instead of Apollo's limited fuel cells it was designed with solar panels, and enough shielding to protect its crew for longer than Apollo could.

Ships are built for a purpose first, and pitched to their financers via elaborate and artistic concept art that explain their story. Its specifications are then designed around turning that story into a reality — a reality that can exist in our inhospitible real universe. Often, the technology for a ship does not exist when its story is written, and the previously-nonexistant technology is developed in service of these lofty goals. Your ship will be the same.

Answer the following questions. For a beginner group, the GM can answer all these questions and bring them to the players. For an experienced group of roleplayers, the whole group can answer these questions together, building out the universe of the story in the process.

5.1 Ship Questions

1. What is your ship's purpose?
    - Is it meant for a large or small crew? [7]
    - Is it meant to carry passengers?
    - Is it meant to transport cargo?
    - Is it meant to travel far, or shuttle back and forth between a few locations?
    - Is it a sprinter or a marathon-runner? [8]
2. What type of fleet is it part of, and how does it fit in with other ships in its fleet?

[7] Methods for calculating mass, volume, and power requirements for different configurations are discussed in more detail in the mechanics section of this chapter. Start with a general idea, to be quantified later.

[8] Trade-offs are discussed in more detail in the mechanics section of this chapter.

3. Was your ship built for this purpose, or was it refitted?
4. How many other ships are in its class?
5. How old is your ship? Has it seen revisions in its lifespan?
6. What is the ship's name, and why was it named that?
7. What is your ship's registration number, and what is the registration scheme of its fleet?

Example Answers for Ship Questions

Let's walk through the process of this story-telling and build an example ship.

What is your ship's purpose? *This is a medical emergency ship meant for rescue and recovery. It is built to be very fast, meaning it is light and not built for much cargo. There should probably be medical facilites onboard.*

What type of fleet is it part of, and how does it fit in with other ships in its fleet? *This ship is part of the lunar fleet, servicing lunar stations and colonies. There are other, heavier ships for passengers and heavy cargo, as well as shuttles back and forth form Earth. This ship rarely, if ever, goes down to Earth.*

Was your ship built for this purpose, or was it refitted? *This ship was refitted from a heavy cargo ship meant for taking cargo from the Earth to the moon. Almost all the pressurized volume was stripped out, leaving the powerful engines, power plant, and control room. Then, a new, much slimmer, crew space was built around the ship's core.*

How many other ships are in its class? *There are only three other emergency ships of this type, though none of them are identical. They're all custom-built after being purchased from surplus auctions.*

How old is your ship? Has it seen revisions in its lifespan? *This ship is twenty years old. It served a long life as a cargo runner then sat on a lunar junkyard for a few years before being rebuilt.*

What is the ship's name, and why was it named that? *Hygieia, afer the ancient Greek goddess of health.*

What is your ship's registration number, and what is the registration scheme of its fleet? ***LXR-03**, which stands for Lunar Rescue 3. All registrations starting with LX are reserved for official operations of Earth's moon, Luna.*

5.2 Engineering the Ship

Now that you've given your ship a purpose, it's time to build it.

Mass, Acceleration, and Engines

The first decision is probably the most difficult, because you have three factors to keep in mind, and everything else depends on it. This is one of the high-level questions that makes rocket science so difficult. Fortunately, ships in this game are unreasonably powerful, solidly in the realm of distant-future *Torch Ships*. A Torch Ship is any fictional craft with very powerful engines that still obeys the general laws of physics.

Even though we shirk the boundaries of realistic engineering, we're going to constrain our ships to real physics[9]. The foundation of rocket dynamics still rests on Newton's fundamental equation:

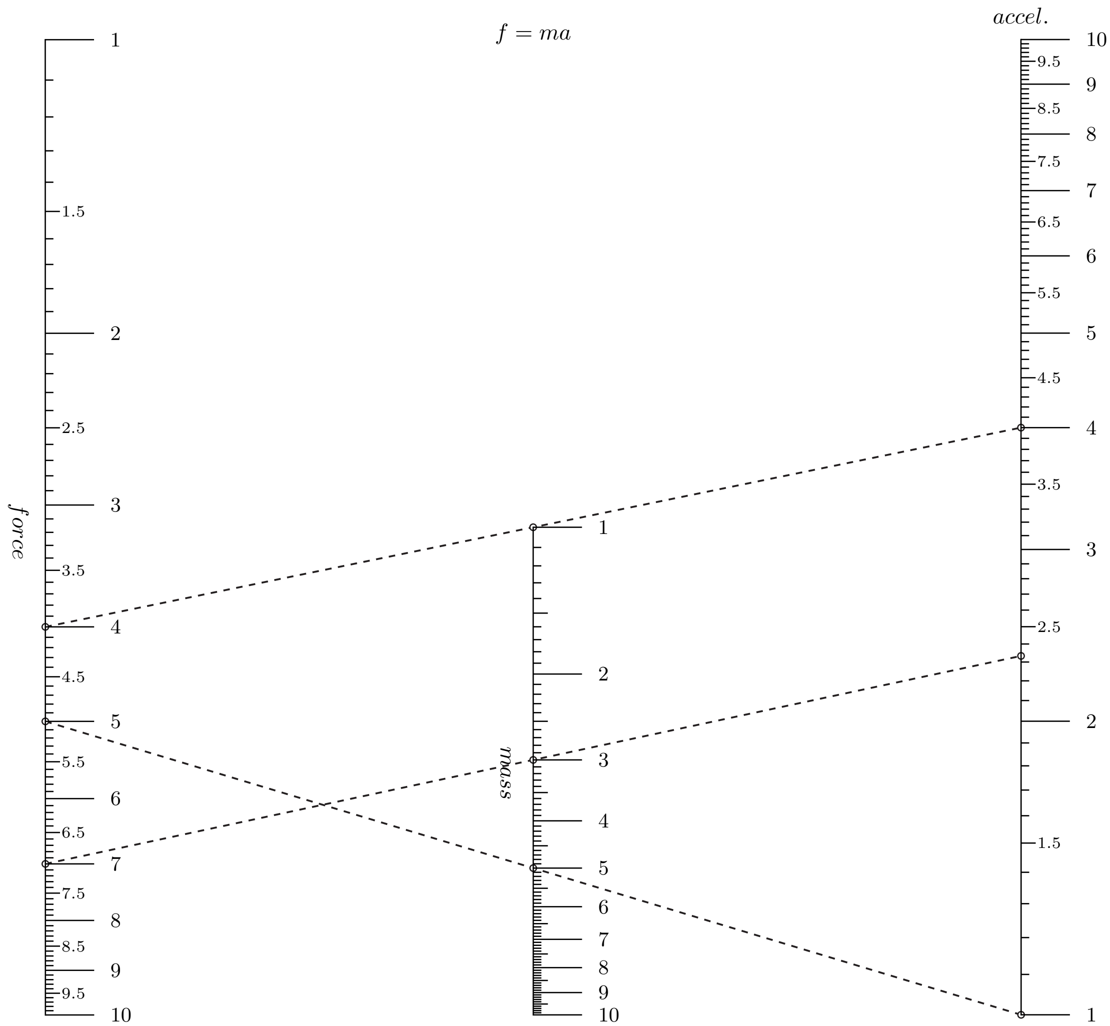
$$F = ma \tag{1.1}$$

In our terms, *m* is the total mass of the ship (systems, fuel, cargo and crew), *f* is the force output of our ship's engines, and *a*, *acceleration*, provides us with change in velocity (*delta-V*) through which we make maneuvers. This acceleration value, double-integrated, will tell us how far can we go. In other words, to push more mass from place to place you need a more powerful engine. To go farther with the same ship, reduce what you carry with you.

To get an intuitive feel for how these three things are related, use a straightedge on the nomogram provided on page 34. Place one point of the straightedge on a chosen number, and rotate it up and down, aligning it with a secondary number. Watch how changing the second value casts the straightedge across different values for the third number.

[9] For now.

Figure 1.2: The relationship between force, mass, and acceleration.



It is easy to see how force changes: the engine is throttled up or down. However, you may notice that the mass of the ship will change as fuel is burned and exhausted out the back of the ship. This, in turn, will cause acceleration to change. We must now invoke the demon invented for precisely the task of space travel: calculus. While the derivation of the following equations and charts will be left to an appendix, understanding the underpinning of orbital mechanics will help make sense of everything else.

TODO: Continue engineering ship section

TODO: Complete engineering ship section

A reaction drive's efficiency as a weapon is in direct proportion to its efficiency as a drive.

-Larry Niven

6 Character Creation

Now comes the time to create your ship's crew. The crew should be populated with varied characters with different strengths and areas of expertise, ready to support all areas of the ship's mission.

6.1 Fiction First, then Mechanics

Some games prioritize concrete mechanics for characters, while others outline more free-form frameworks to aid roleplay. Exotic Matters is in the latter category. You will first create the story behind your character, then choose a gestalt number and skills based on that story, in order to integrate it into the game.

A backstory should include the location and culture you're from, your job on the ship, particular life skills and achievements, and an particular glaring want or need in life.

Example of a Backstory:

> Maverick is a human from Terra. He grew up in the state of Iowa in the North American Union. He is on the *Stone's Throw* to be an envoy, with a specialization in cultural traditions. He hopes to find his uncle who went off with an interstellar mining guild fifteen years ago.

This example includes a number of good elements. It includes a species and heritage, providing a cultural background. The presence of the term *North American Union* implies a different political situation than the contemporary. It also has a job to help you choose skills. Try to keep it short, but rich. Specific details are good, but don't bog down your character with too much. Create only what you need to play out the story, and don't be afraid to discover more as you go, adding as time goes on.[10] Note the last sentence: it contains a goal unrelated to the mission of the ship. This brings us to the next section, which is choosing your **Objectives**.

6.2 Objectives

It will also be useful to have an overarching goal or development that your character may have during the story arc. This major goal is called a **Superobjective**[11]. This superobjective may be something like *reinvigorate my love and wonder for the universe* or *find my long-lost brother* or even *exact revenge on the asteroid-mining mogul who cost my mother her life*. These goals should carry an emotional component, because they are *important* to your character. Don't force your character to go through these changes or complete their superobjective, but take opportunities to explore them. Your character doesn't even have to be aware they have this need

[10] If you have any formal acting training, what we're doing here is exploring the *given circumstances*.

[11] Again, a term taken from the theatre.

Roll	I want to...	so I can...
1	find my prodigal sibling	bring them home.
2	confront an asteroid-mining tycoon	arrest them.
3	find long-thought-dead parent	tell them my dark secret.
4	discover who built my genome	ask them the blessing I am owed.
5	escape my overbearing parent	prove that I could make it.
6	meet my clone	find out the truth about my family.
7	locate my ex-best friend	give them a token I swore to deliver.
8	meet a distant cousin	uncover their fraud.
9	talk to God	ask a question only they can answer.
10	locate an ex	find if a rumor is really true.
11	meet an alien prophet	beg them for forgiveness.
12	capture my evil twin	bring them to justice.

Table 1.1: Motivations

or want, but should have a tendency toward completing it. If you make your GM, aware of your character's superobjective, they may integrate more opportunities or encounters into the story to help your character along.

Each character should be given at least one objective. More complex characters in the foreground can have two or three, while minor characters that get played less frequently can have only one. These are personal goals with an emotional basis in who your character is. Superobjectives can benefit tremendously if they're based in a relationship — much of what people *deeply*, irrationally want is just a proxy for resolving problems in relationships.

The conflict should probably not be between crew members. Crew members can become player characters at any time, and unless you know and trust the other player very well, inter-party drama can spill into real life and cause real-life issues. Advanced players, comfortable with respecting each other's limits can review the player/player conflict section of the safety tools section.

You can roll a d12 on each of the columns of Table 1.1 to determine your character's superobjective, or create your own.

Some combinations may be a little nonsense, so you can reroll or just choose another one if a combination doesn't make much sense.

Take a step forward and back from your superobjective: what events led to you wanting to do this so badly, and what do you think you will get out of achieving it? What smaller goals and steps will your character take in pursuit of these ends? These smaller steps are called **Objectives**. List a few objectives in service of your superobjective.

Some of your objectives should be able to be accomplished within just one session.

Example of Objectives:

> Say that you've selected and built out your character's superobjective as "Confront the asteroid-mining tycoon who exploited my Lunar colony for decades, caused my mother's death, and bring him to justice." The following objectives might support that superobjective, or simply harmonize with them:

- Find where he works how by talking to miners in the asteroid belt.
- Bait him into a trap by forging a transmission from probes in his mining operation.
- Help support a strike against a different mining company, just because you empathize, even against your captain's orders.

Let's enumerate another objective list, based on the superobjective "Escape my parents and show them I can make it on my own."

- Join an interplanetary ship where I'll be away from them for months at a time.
- Vie for promotions and commendations whenever possible aboard my ship.
- Seek approval from authority figures.

Note how the third item in both cases does not directly support your goal, but aligns with your need. Your superobjective can subconsciously influence your behavior.

Now, think of how the problems your character is trying to overcome could be represented by a science-fiction metaphor. Discuss this with the group, and especially the GM. The GM will take notes and may choose to pull from your superobjective when planning story. The metaphor in sci-fi often serves as a proxy for interpersonal conflict; solving the major textual conflict can teach your characters how to solve internal and interpersonal conflict. Your character may come up with a new solution based on these new experiences, trying a new tactic, learning to manage a trauma, or forgiving someone they still care about. There is no guarantee your character can resolve this conflict during the campaign, but you may just have the chance.

Another note: A lot of stories are about change and irony. Maybe the completion of your superobjective doesn't satisfy your character like they thought it would. Maybe they change their standards and learn to be happy with never knowing some truth, or never getting what they wanted. Maybe they do get it, but it costs them *everything* else important to them like other friends, honor, or their own identity.[12]

To take our *exacting revenge on the asteroid-mining mogul* objective from earlier, and play it out, perhaps your character realizes they cannot bring themselves to commit murder, and even feel compelled to save him when he's in danger. Perhaps your character *does* kill him, but ends up leading a violent gang and falling through the morals-event-horizon, never to be the same.

[12] Also known as the principle of *Yes, But...*

Gestalt number	Tech	Sense
3	83%	25%
4	75%	33%
5	67%	42%
6	50%	50%
7	58%	58%
8	42%	67%
9	33%	75%
10	25%	83%

Table 1.2: Gestalt Number vs. Probabilities

Once your character has achieved an objective, replace it with a new one, and **mark one XP**. You should act on any new information or consequences that have cropped up due to actions you took to achieve your objective.

Likewise, if you achieve your superobjective, **mark three XP** and choose a new one. If your character is now relatively content, perhaps they can step out of the story or take a lesser role to allow other characters to pursue their objectives. With the seeds of story planted, we can move on to the mechanics of your character.

6.3 The Gestalt Number

There is only one stat for a player character in EM, which lies along the Sense and Tech axis. It's pretty simple: the closer you are to sense, the better you are at intuitive tasks and experiential training, etc., and the closer you are to tech, the better you are at tasks that require overt knowledge, cognitive reasoning, and so on. But both are on the same axis, and your character keeps track of just *one* number. We'll call this your **Gestalt Number**.

Whenever you take a *risky action*, the GM may decide to resolve the risk with a die roll. You will roll a twelve-sided die (a.k.a. a **d12**). If you're rolling for a tech action, then you succeed if you roll your gestalt number or higher. But if you're rolling for a sense action, you succeed if you roll your gestalt number or *lower*. So the more likely you are to succeed on tech rolls, the worse your ability to succeed on sense rolls, and vice-versa.

The gestalt number can be as low as 3 and as high as 10. This means the greatest chance of base success you can have for a tech or sense roll is 75%, with the opposite type of roll having a 25% base chance of success. A complete comparison of base success probabilities is shown in Table 1.2.

Example of Choosing a Gestalt Number:

> Let's take Maverick from earlier. Since he is meant to be an envoy, Maverick will likely be seeing action in social and political situations – sense rolls. Because of this, most of his rolls will succeed if they are less than or equal to his

gestalt number. Therefore, a high gestalt number will be advantageous. Let's choose 10. Maverick will heavily favor social skills and frequently succeed. However, if he tries to do anything technical like fix a broken power junction, he probably won't be able to do it.

Alternatively, Maverick could have a small technical background. We could instead choose 8. This would give much better chances for success in an emergency technical situation. However, his skills in diplomatic situations will suffer. Fortunately, there is a way to offset this for specific situations: skills. In the next section, we will learn how to choose skills to aid our characters specific job, to both complement a character's strengths, and make up for their weaknesses.

6.4 Choosing Skills

To succeed on more rolls, a player character can gain **Skills**. A skill provides a bonus when rolling for a specific type of action. Skills can nudge a roll toward success by one or two. Tech skills *add* to your roll, while sense skills *subtract* from it. Thus, you can specialize in skills and become particularly good at them.

Skills can be learned at two levels: level 1 is **Learned**, and level 2 is **Mastered**. A learned skill skews your roll toward success by 1, and a mastered skill skews your roll by 2.

When you create a new character, give that character two skills at the learned level, and one skill at the mastered level. Think about how these skills will interact with the character's gestalt number and how they integrate with that character's story.

A complete list of skills can be found in the *skills* section of the *Details of Play* chapter.

Example of Choosing a Skills:

Let's go back to Maverick. He is an envoy, and we want to give him skills that will help him as a diplomat. There's an obvious choice for his Mastered skill: Diplomat. Diplomat will give Maverick a slight edge when trying to convince people of power to do something.
Next, we must give him two skills at the Learned level. Citizen and Historian look like promising skills, as they will give Maverick knowledge and help him infer more information about the cultures he may be liaison to. This makes Maverick an excellent specialized character, but he will need support of other members of his crew.

Alternatively, we could give him one or two skills that give him tech skills for particular situations. For instance, Needle-Eye may help Maverick notice and remember small details about the people he talks to, or better evaluate circumstances in his contacts' offices and workplaces. Strategist would give him an advantage every time he works according to a plan he detailed before acting. If we choose both, Maverick will be more generalized, but be less totally competent at his particular job.

Continue to create additional secondary crew members to fill your ship's manifest. Not all of them have to be as detailed as your primary player characters, but they should have enough detail to act as NPC crew members. Give these extra characters to the GM. Players may choose to switch to playing these crew members at a later time (see the *Crew Pool* for details).

6.5 Life Aboard the Ship

Now that you've got a ship and crewed it with the best, it's time to determine what life aboard the ship is like. Space is very big, so there are long intervals of time between destinations. The ship is bound to develop some culture and customs.

Consider what day-to-day life would look like, keeping in mind the types of crew members your ship is likely to have. Ask the following questions of yourselves and your new crew members:

- Is this a good ship?
- Is the ship reliable?
- Is this ship comfortable, relatively speaking?
- Are you happy about being aboard this ship?
- Why were you chosen to crew this ship?
- Is the mission of this ship important?
- Do you get along with your fellow crew members?
- Does the crew have a strong sense of camaraderie?
- Does the crew eat meals together, and is there room to do so?

You can generate some ship customs using Table 1.3. Roll two or three to add some flavor. Again, not all combinations may make sense, so reroll as much as you want.

Sometimes, even the most expensive equipment doesn't work properly. At times like those, even the most rational and level-headed crew members may resort to minor rituals and superstitions concerning problem equipment. Come up with one or two pieces of equipment that frustrate crew members, and the irrational things they believe about them, or roll on Table 1.4.

Roll	When...	the crew...
1	the ship lands at home	makes a special meal.
2	the ship lands someplace new	has the captain make a speech.
3	the voyage is halfway done	holds a contest of strength.
4	it's someone's first voyage	holds a game tournament.
5	the crew gets too restless	shares drinks together.
6	twenty-four standard hours pass	ignores all rules and regulations.
7	everyone gets their pay	spends money in frivolous ways.
8	a ship record is broken	composes songs of the ship's exploits.
9	someone saves the day	give each other minor gifts.
10	two crew members get into a relationship	pulls a prank on someone.
11	a conflict needs resolving	holds lively debates and discussions.
12	-ever possible	gives someone a new nickname.

Table 1.3: Ship Culture

Roll	Issue	Part
1	If you talk covetously of another ship ... malfunctions.	a certain light
2	You need to operate ... just right.	one problem engine
3	We can never replace ... or things will go wrong.	the radio
4	You should never touch ...	a particular seat
5	You have to toggle ... an even number of times.	a particular console
6	... is probably haunted.	your personal log
7	... has to be reset every day.	your ID card
8	If you touch ... you will have good luck.	the reactor
9	... only really loves a few people	the radiator
10	... will act up if (and only if) you're angry.	a certain button
11	... will break every time everything else works.	your EVA suit
12	... only works well if you pretend you don't care.	a random system

Table 1.4: Ship Superstitions

7 Rules of Play

7.1 Skills

To succeed on more rolls, a player character can gain *skills*. A skill provides a bonus when rolling for a specific type of action. Skills can nudge a roll toward success by one or two. Tech skills *add* to your roll, while sense skills *subtract* from it. Thus, you can specialize in skills and become particularly good at them.

Skills can be learned at two levels: level 1 is **learned**, and level 2 is **mastered**. A learned skill skews your roll toward success by 1, and a mastered skill skews your roll by 2. A skill must be learned before it is mastered. It costs 3 XP to learn a skill, and 3 XP more to master it.

When you make a roll, check your character sheet and see if any skills apply. If you think they do, ask the GM if it applies, and if the GM determines that it does, add it to your roll according to that skill's level. The GM has final say over which skills apply. Only one skill can be applied to a roll at once – skills don't stack.

7.2 Sense Skills

Botanist Growing, identifying, and finding plants. Reasoning about the properties and biology of unfamiliar plants.

Culture Understanding and operating in living cultural situations, even unfamiliar ones.

Diplomat Persuading politicians, businesspeople, or leaders.

Firefighter The instinct for managing emergency situations and equipment malfunctions (including fires).

First Aid Stabilizing and comforting wounded people. Use may reduce an injury from Critical to Minor.

Linguist Decoding and learning local languages.

Orienteer Navigating and traversing unfamiliar, unstable, and alien terrain

Pilot Making risky maneuvers that requires human piloting.

Reverse Engineer Reading unfamiliar schematics and operating unfamiliar machines.

Sharpshooter Accuracy in any task requiring good aiming or targeting.

Socialite Orienteering and navigating unfamiliar terrain.

Survivalist Finding necessary resources and shelter in any situation, urban or wild.

7.3 Tech Skills

Astophysicist Studying the behavior and processes of distant natural objects, or getting insight on the behavior or nature of catalogued and uncatalogued objects.

Chemist Observing artificial and natural chemical processes (including at a distance through spectrography) as well as performing checmical procedures and experiments.

Hacker Operating computers and using them for unusual purposes.

Historian Learning about, inferring, and interpreting local history.

Mechanic Repairing and modifying familiar machines.

Medicine Performing general medicine, surgery, and health checks. Use may reduce an injury from Critical to Minor.

Needle-Eye Observing environments, objects, physical attributes of people, and visual details in many situations.

Psychohistorian Reasoning about cause, effect, and long-term consequences in large-scale political and social systems.

Radar Use the ship's radar and other instruments to find information about other ships' velocity, position, rotation, mass, temperature, and other factors.

Ship Guy Understanding, fixing, and tinkering with ship mechanisms and systems of a mechanical or electrical (but not electronic) nature.

Strategist Executing plans made beforehand.

Surveyor Surveying, mapping, and identifying objects (including terrain and structures) on distant or nearby celestial bodies.

Double Skill Checks

You may occasionally attempt an action that is not *impossible*, but incredibly unlikely. Even a person of considerable skill would have to be incredibly lucky or particularly focused to achieve. In such cases, the GM may choose to require *two* rolls to succeed. Often, the two rolls will require rolls of opposite types: one may be a Tech roll and the other may be a Sense roll, as many difficult problems require a great deal of mental knowledge as well as good instincts and quick reaction. This may make it difficult for one character to achieve both.

Fortunately, a good ship has a wide variety of crew members with differing strengths, so any crew members present may take on one of the two rolls, allowing the other crew member to take on the roll they are more likely to succeed. Some double skill checks may even be done remotely, by radio, if reasonable.

Example of a Double Skill Check:

> **Virgil (GM):** *The space station* Cygnus *has no power, and is rotating out of control.*
> **Sayan (playing Calisto):** *I'm going to try docking anyway. That's a Pilot skill, right? Sense.*
> **Virgil:** *That's correct, but this is a particularly tricky docking attempt. You can't do this on your own — you'll need more information from the ship's radar and other instruments to track* Cygnus' *relative motion. This is gonna be a double skill check. The other is going to be* Radar. *That's a Tech roll.*
> **Sayan:** *Yikes. My gestalt number is nine, so I'm probably not gonna succeed on that.*
> **Josie:** *I've got it. I'm playing Dr. Grace, who not only has a gestalt number of three, but also has* Radar *learned.*
> **Virgil:** *Go for it.*
> **Josie:** *I hop on the console and punch up the radar, external cameras, and other sensors. I start calling out relative rotation and distance to the docking port.*
> **Virgil:** *Give me a roll.*
> **Josie:** *That's a five. Even without the skill, that's a success!*
> **Virgil:** *Fantastic. Callisto, with Dr. Grace on the radar calling out your relative velocity and other info, you're able to make more precise maneuvers. Roll your Pilot skill check.*
> **Sayan:** *That's a two! We got it!*

7.4 Failure

If you roll, and fail, then something goes wrong. It's up to the GM to determine *what* goes wrong. The GM should use their best judgment to determine the severity of what happens. If, for example, a shuttlecraft's instruments are out, a player may try to land by the seat of their pants, and choose to roll with a pilot skill, aiding that roll. If their gestalt number is 4, and their pilot skill is 2, but they roll a 1, they get a total of 3 and they fail. However, it might be cruel to TPK (*total-party kill; killing every player's character*) by smashing the shuttle into the ground and end the game right then.

Instead, the GM may choose some consequences. Perhaps the shuttle lands far off-course, and has its landing gear damaged on touchdown, preventing the players from taking off until they repair it. Perhaps they crash-land in someone's barn, making the locals upset. Depending on the severity of the failure, and how much pity the GM wants to take on their hapless players, the consequences could be lesser or greater.[13]

7.5 Injury

Injury in Exotic Matters is serious, because human beings are fragile and squishy. Though medical technology in the future has come far, it will not be easy or quick to recover from an injury, and some critical injuries will be fatal if left untreated. Extreme circumstances will result in instant death.

Injuries should mainly result from poor player choice. Some styles of play may include *Red Shirts*, which are minor crew members who die to demonstrate imminent danger, but this style of crew sacrifice should be negotiated with players beforehand.

Injuries come in three levels: **major**, **minor**, and **critical**. There are no mechanical effects particular to specific types of injury in the same level; restrict activity as makes sense for the narrative. Successful use of the *First Aid* and *Medicine* skills can reduce the severity of an injury from Critical to Minor.

When a character is injured, they are simply taken out of play for the duration specified by the injury, and restored to play when recovered. Exotic Matters has no written mechanics for playing currently-injured or characters – as soon as they get to safety, they are simply out of play until they recover.

Minor Injuries Minor injuries occur when something non-life-threatening happens. A character may temporarily lose use of a broken arm, minorly-burned hand, or be weakened from heat stroke. A minorly-injured character may be out of play for one day to one week.

Minor injuries include:

- Getting into a bad barfight
- Getting hit by a loose object *(Foreign Object Debris, FOD)*

[13] GM Note: Be sure not to let a failure halt all action; that kills the pacing of the story and morale of your players. Players *do* enjoy a challenge when they're forced to fight harder, but remember that failures get them into more trouble, not just stop them in their tracks.

- A few minutes close to a strong radiation source
- 9G or greater acceleration for any period of time
- 6G or greater acceleration for more than a few seconds
- Being exposed to the vacuum of space for less than ten seconds

Critical Injuries Critical injuries occur when something life-threatening happens. A character may receive major radiation poisoning, pass out due to exhaustion and overexertion, or even be shot. A critically-injured character will die if left treated for too long, and with treatment may be out of play for one week to one month.

Critical injuries include:

- Colliding with the ground at greater than $30m/s$ unprotected
- Getting hit in the head by FOD and receiving a concussion
- Dozens of minutes close to a strong radiation source
- 15G or greater acceleration for any period of time
- 9G or greater acceleration for more than a few seconds
- Being exposed to the vacuum of space for no more than ninety seconds
- Getting shot

Fatal Injuries Fatal injuries are extreme forces and energies imparted onto a human being that cannot be survived. GMs should not dole out fatal injuries lightly or randomly, and they should always be the consequence of poor planning or mistakes on the players' part. They should not be the result of poor dice rolls in normal circumstances, but rather the result of deliberately choosing an impossible or harmful action, or else the result of failing a roll on some extremely risky decision players make. A fatally-injured character may be out of play forever.

Instantly Fatal injuries include:

- Colliding with the ground at greater than $30m/s$ unprotected
- Colliding with the ground at greater than $100m/s$ in a seat
- Being struck by a slug at orbital velocities
- Dozens of minutes close to a strong radiation source
- 20G or greater acceleration for any period of time

- 15G or greater acceleration for more than a few seconds
- Being exposed to the vacuum of space for ninety seconds or more
- Passing the event horizon of a black hole[14]

The GM has final judgement over when a character becomes injured, and what level of injury occurs.

7.6 The Crew Pool

A ship has many crew members, but only a few players will be at the table at a given time. Exotic Matters allows a ship to have many crew members, all of which are playable by players during the course of a game. This is called the **Crew Pool**. The Crew Pool is a stack of character sheets for characters that aren't currently being played by any players, kept in the center of the table and within reach of the GM. These characters may be out-of-frame for the scene, or played by the GM as supporting NPCs.

At any scene change, any player can swap their character for one in the Crew Pool. The player picks up this new character sheet, looks at the gestalt number, and skills, then reads the character's backstory and motivation. From there, the player will try to embody the new character, following their new superobjective. When a character is being played by a player, that character can grow, change, and pursue their objectives. When that character is being played by the GM, the GM will play that character as a more minor force, who does not take center stage to pursue their goals in major ways.

Characters can be shared between multiple players. The same person can keep switching between the same two or more characters, and a character can pass through the hands of everyone at the table as the story goes on.

The Crew Pool also allows the alternating progression of an A-Plot and B-Plot. One group of crew members can be on a surface expedition, while another remains on the ship, and everyone at the table can participate in both teams as play switches back and forth between the two plotlines, swapping their character sheets with each transition. Whenever a group splits off from the ship, it may be helpful to include other players by adding characters to the away team from the Crew Pool for them to play.

[14] Probably.

Chapter 2

The Universe

1 Mercury

The innermost planet of the solar system, a rocky and desolate selenoid.

Orbital Parameters

Semi-Major Axis	5.791×10^7
Eccentricity	.240846
Argument of Periapsis	29.124°
Longitude of Ascending Node	48.331°
Mean Anomaly at Epoch	174.796°
Inclination	7.005°

Other Parameters

Gravity Factor	$2.26322014 \times 10^{13}$
Mass	$3.3911 \times 10^{23} kg$
Synodic (solar) Day	176 days
Sidereal Day	58.646 days
Sidereal Orbital Period	87.969 days
Surface Gravity	$3.7m/s^2(0.38g)$
Escape Velocity	4.25 km/s
Equatorial rotation velocity	3.026 m/s (10.892 km/h)
Blackbody Temperature	437 K (164 C)
Radius	2,439.7 km

Common Knowledge

Mercury is a tiny terrestrial planet, rich in metals, with no atmosphere. Its solar day is twice its year, and it is the closest planet to Sol. Due to ready materials and proximity to the sun, Mercury mostly sees use as an energy production facility. The planet is swarming in mining equipment and factories, which build solar reflectors and collectors. These satellites are then launched via railguns into orbits around the sun, where they collect energy to return to the planet. This system is known as the Hermian Swarm. From Mercury-based power routing stations, energy is beamed via carefully-aimed masers to power substations throughout the solar system. There is a small excess of power generated, which is beamed away into the void.

Energy cost remains low as long as Mercury Station keeps running. Disruptions are infrequent, as most of the automatic heavy equipment and production line is self-sustaining. The only population is its minimal maintenance crew, who live on its dark side, in a crawling building called The Mother that creeps around the planet to stay in the night. Pay is good, but conditions are cramped and tensions run high.

Death is more common from work accidents here than anywhere else in the solar system.

A spacer's life is dangerous, and try as they might to avoid it, mortality must be faced. Backgrounds and beliefs vary widely, but there is a method of burial in space that has become a common ritual among veteran spacers. This tradition is based on the idea that a spacer should never stop exploring, even in death. If a spacer dies on a mission, they will often have made clear their wish to be buried in space. This involves encasing their body in a minimally protective barrier equipped with a small solar sail. Their ship then sends out a transmission to The Mother on Mercury, where there is a designated power relay tailored specifically for this purpose. The ship ejects the wrapped body at the ideal trajectory and the Swarm provides power to eventually send it out of the solar system, to never stop exploring outward.

Among the many power relay jobs in the Hermian Swarm, the Last Watch is one of the most sought after, especially among those who previously spent time on ships where such services were rendered. The meaningful opportunity to provide the final boost to a fellow spacer is never taken lightly, and never given to a young greenhand who does not grasp its weight. It is also not a position that is held for long. Every month or two, one of the few positions will open up and the line to sign up for the job lottery will stretch through the entire relay section of the Mother. There is never any unpleasantness when the accepted applicant is announced; rather, they are congratulated and thanked for their service. They will answer the tearful calls from ships who have lost crew members for the next few months until they decide it is time to step down from this unrelentingly emotional job for their own health.

Locations

The Mother Mercury's moving repair station is often referred to as The Mother. Some say it with an unspoken (or emphatically spoken) "-fucker" at the end, but it is generally lovingly seen as an enduring berth of safety for those who facilitate the lives of the rest of the solar system. The giant station on treads moves at just under 10 km per hour to always remain at the midnight point on the slowly-rotating planet. Control is somewhat bureaucratic, but fiercely democratic. The industrial nature of the facility fosters a union-town type of society, where decisions are made in the workers' best interests. Any attempt to run the facility with priorities other than those worker's welfare in mind does not last long – the thin margin of survival here means any deviation from safe protocols results in people dying, and any person or process responsible is quickly stripped of power or corrected.

The Old Mother A previous crawler lies along the same latitude as The Mother's eternal march around Mercury. Things don't decay in vacuum, but you wouldn't trust it to hold pressure now. Version one, or maybe two? It hardly matters, as none of the original parts remain either way. It's a timeless museum with no visitors; if the computers still work, there is probably a whole history to be recovered.

The Hermian Dyson Swarm Colloquially called The Swarm, this constellation of tens of thousands of satellites collects power from the sun and beams it to the rest of the solar system. Thin, light, reflectors make up a majority of the swarm, direction focused sunlight to a smaller band of collectors that beam that energy back to Mercury or remote targets in the rest of the solar system via masers. People do not service these satellites directly, but through a small army of drones. Some xenoanthropologists believe that the periodic obscuration and dimming of the sun by the rapidly-moving swarm will make the presence of intelligent life visible from a great distance and that measures should be taken to lessen the effect for safety – but most people dismiss these concerns as paranoid.

Antimatter Refineries High above Mercury are several solar collectors that use the energy they receive to conjure antimatter from the quantum fields, carefully assembling antihydrogen atom-by-atom by smashing particles together at near-light-speed. These refineries are far from any humans, as even the slightest containment breach would spell disaster for anyone within thousands of kilometers. Of course, these locations are monitored at all times from afar.

First Sight

Dropping over Mercury, the landscape is reminiscent of Luna: gray, dusty, and pock-marked with craters. Yet the effect of the overwhelming presence of the sun cannot be understated. The day side shines more brightly than the brightest day on any other world. The night side is surprisingly dark - the light from the stars provides little illumination, but the corona of the sun can be seen peeking the horizon from certain spots near the dawn: a ghostly suggestion of a much more powerful presence hidden from view.

The huge pits of strip mines pock-mark the surface. Looking at first like small craters, only the tiny dots of yellow mining drones give reference to the huge diameter of these open pits. Giant automatic tractors crawl the winding roads up out of the pits, delivering their payloads to the surface grids of refineries and factories that cluster the surface.

Closer to the equator, you see a large railgun, a series of big electromagnetic rings through which run small tracks. In an instant, a small slug is accelerated along the track and slung into the sky, where it quickly diminishes into the faintest star, then into nothing. This is one of the solar collectors of the Hermain Swarm. This dead rock is being mined to build enough solar collectors to let humanity do nearly anything.

A few spots across the dark night side glow like day; these are the receiving collectors that take some of the power generated by the swarm to power the earth-movers and factories that add to the same swarm.

Around the equator, a corridor remains clear of machines and strip mines. This is the route taken by Mercury's controller station, the only place on the planet with a human presence. All the engineers on Mercury live in that grand crawling base, the Mother, which travels at a walking pace to keep its place on the night side of the slowly-turning planet.

Falling closer, you see the track left by the Mother before you see the base itself; many tracks remain untouched from the dozens of circumnavigations the Mother has made over its lifetime. But sure enough, the large base comes into sight, its motion invisible at this distance. In actuality, it crawls ahead on great treads at just over ten kilometers per hour.

A pressurized rover, much like what might be seen on Luna, returns from some task of investigation or equipment repair. It drives up a ramp that nearly scrapes the ground and attaches itself to its mother.

Plots

Swarm Takeover

Governments may have acquiesced to the independence of Mercury, but corporations rise and fall and often have ambitions beyond their years. The Lancer Corporation, a vulture capitalist fund based on Earth, has started a years-long operation to infiltrate the strongly independent population on The Mother and eventually engineer a takeover of the solar system's energy production. The citizens of the station are unaware of this plot, but one of the conspirators has had second thoughts and may be the source of an anonymous tip you received when you arrived at the station asking you to look into the matter.

How to Introduce Players receive an anonymous tip suggesting they look into connections with Lancer Corp. on the ship's text communication: "Some workers may have connections with Lancer. Be cautious." Tracing the signal, based on direction and time of receipt, it could only have come from the Mother, obviously, but no further specificity can be determined.

Soon, the ship receives an encrypted message from Lancer. It asks if the players would be willing to receive a program and leave it on data tapes stowed away in a specified location. If they refuse, Lancer ceases all communication. The program is obscured and not much analysis can be made. If they accept, they can leave the program tape where specified, and any monitor will find Nyles taking it from its hiding spot. If Nyles is caught, the Space-to-Surface plot instantly begins as he explains his plan.

It Develops... Lena has a hand in all the communications systems so surely, she'd have to be in on any conspiracy, right? Some members have vague notions that Nyles once worked for Lancer, or maybe his father owned some shares in it. Old Sly worked for many space companies, including a now-defunct competitor to the Hermian Swarm called Starscoop Inc. many years ago. He held thousands of shares and lost them all when it went bankrupt.

Mya Jensen eventually gets desperate enough to stop Lancer that she goes to Torson, but he doesn't believe her story and is afraid she is trying to add to her leverage over him. She flees into the bowels of the Mother before he tries to further silence her, and decides to keep a low profile and stay with the Hemley family. Jet Hemley is a fiercely adored team lead, and his wife has fed almost every person on the station at some point, so when Jensen tells them of the danger and they take her seriously, awareness in The Mother begins to grow.

Without our Heroes' Help... The improbability that one company could take over the entire Hermes operation works both for and against those who are trying to stop it. On the one hand, it is difficult to convince a majority of the people on the station of the danger, and most end up dismissing it until they see proof. On the other hand, it is truly an improbable accomplishment for Lancer. When Torson lashes out again at Jensen, Miller uses it as an opportunity to make a power grab. He quickly installs Lancer operatives in key positions to start implementing the takeover. As this unfolds, however, a few people are quick enough to recognize what is going on because of Jensen's warning, and are able to stop some of the system lock-outs that Lancer agents attempt to make. Lancer tries to leverage the systems it does control to gain concessions from the station, but one group of Hermians is able to get a message to Earth. The Russian government (where Lancer is based) forces Lancer to order its agents to stand down, but not before those agents have starved the group that warned Russia of oxygen, causing permanent brain damage. Lancer agents are rounded up and forced off the station, and both Lancer and The Mother will attempt to recover from the ugly standoff.

Strongly-Worded Maintenence Request

The construction of The Mother and its systems was made with double and triple redundancies, and is under constant surveillance and maintenance. The integrity of the drones of the Swarm is much harder to maintain, so extensive care is taken to ensure things go right the first time. And yet, things inevitably go wrong. The latest update has been a patch to the drones' navigation instructions to adjust for the increase in drone density as another batch is about to be fired into orbit around the sun. Because some of the drones are on the other side of the sun, this update has to be relayed through the drones themselves, chained across their orbit. However, something in the incredibly complex maneuvering instructions was miswritten, and the error could mean the gradual destruction of every Hermian drone if it is not somehow corrected.

How to Introduce Players see increased activity in the drone manufacturing facilities on their original approach, indicating the upcoming introduction of another set of drones to orbit. On the day of the launch, players are warned by Lena Bersch to shut down communications and sensors prior to 20:00 hours to avoid interfering with the priority update transmission.

The next morning, players run into Mya Jensen or Lena Bersch (whoever they are most familiar with) in extreme distress, and are told that the drones have been sent out but the software update has a flaw that has stopped it from transmitting beyond the first drone - which is now racing away from The Mother in its solar orbit. If the players have gotten to know Jensen/Bersch well, they may be asked if they can help. If not, the players may have to volunteer themselves if they want to help (or receive further urging from other staff, at GM's discretion). The Hermians need the fastest ship available (yours) to reach the drone and correct the update before it goes out of range. If it leaves without transmitting the update, the new additional drones will cause the rest of the drones to variously deorbit into the sun or jettison themselves out into the solar system, and there will be little to nothing left of the Swarm.

It Develops... Because the drone is racing away from the station, time is of the essence. The only way the Hermians can think to fix this is by reaching the intended "patient 0" drone and manually installing the retransmission add-on.

If players choose to take off right away, they will be able to catch up with the drone more quickly, but may face consequences of unpreparedness - a team member may not be onboard at the moment, the ship may be underfueled, there may be supplies taking up space where the drone would need to be brought aboard; any number of complications determined by the GM and/or dice rolls could ensue. If they take time to make sure they are prepared, there may be consequences for letting the drone travel farther away - they may need to push the ship beyond safe limits, the ship may have to burn extra fuel/other resources, or they may have to pull off complex maneuvers to catch the drone.

Without our Heroes' Help... Lacking a ship fast enough to catch the drone, Hermians are forced to wait for the next passing drone to transmit the correct update. Though the update is transmitted to most of the drones, it is off of the planned schedule; the new drones have already been launched, and will disorient the existing drones enough to send a number of them askew and out of their orbits - it is too soon to tell how many. Because of this, the stream of available power to the system is greatly diminished. The players will likely face (at the very least) delayed travel times because of the ordeal. If the players have openly refused to help, they will have a hard time building relationships with anyone on The Mother, as this has made everyone's life harder and more stressful until enough replacement drones can be launched.

Space-to-Surface

It's unthinkable that anyone would turn the Hermian Swarms' masers onto human life... so unthinkable that some days it's all Grip Torson can think about. There are system interlocks in place, and even he doesn't have direct control over their orientation. They won't turn on any planet or ship transponder. Every command sent to the masers is logged by three separate eavesdropping stations.

So when Nyles wants to turn the masers onto the surface of the sun, there shouldn't be a problem – all he has to do is get a few approvals, and he can begin his program. What he's not telling anyone is that the Lancer Corporation requested this program, which will then be able to create a solar flare on request - even a much bigger one than designed.

How to Introduce When the players are talking to Grip, Nyles arrives to get approval for a new program. Have him in a bit of a rush, and just slightly pushy. When Grip refuses to sign anything or provide his access key without a full explanation, Nyles quickly and casually explains that he plans to turn the masers onto the surface of the sun to lift a jet of stellar material which will fly out toward Earth, but well out of the safety zone. Besides, Earth's strong magnetic field will protect it in case anything goes wrong. Other drones will help create magnetic corridors to help direct the column safely. He will need temporary control of some masers to do this.

It Develops... To examine the program, players will have to do espionage or else get Dusty and/or Rusty's trust and help in obtaining a copy of the program. Examining the program reveals it has no safety measures; additionally, it lets those masers be controlled remotely, not just from the Mother.

Lena Bersch can help the players log Nyles' communications to his Masers if they ask; she will find that he is retransmitting a signal he receives from the direction of Earth.

If asked about any of this, Mya Jensen will casually deflect, telling the players that there is nothing really to be worried about; Nyles may be at odds with the popular opinion, but he's not really a bad guy.

Without our Heroes' Help... Nyles declares the test a success, and continues to use the process occasionally, when there is a surge in energy demand.

He continues to hide the sinister potential for the redirection, and whoever is directing his actions from Earth maintains the option of using it as a weapon.

Espresso Depresso

The old-school espresso machine is practically the centerpiece of the Mother's mess hall. A peace offering from Earth back in the early days, it was sent at tremendous expense all the way down to Mercury. It has served the workers for more than one hundred years, being fitted into each new iteration of the Mother specially.

Unfortunately, the big brass beast seems to not be working. And it's hard to diagnose - the blasted thing has had so many modifications to its mechanisms that no one alive knows how it all works. Rusty and Dusty have been trying to hunt down the person who broke it, but nobody will fess up. They've gone in circles long enough they're even accusing each other...

How to Introduce Have various NPC workers on the Mother complain about the lack of good espresso, or the poor quality of packaged coffee pouches.

It Develops... Upon player investigation, the problem may become evident to an engineer or mechanic who is familiar enough with your ship: it just so happens that the espresso machine was modified to use a fuel injector plate from the very same model of attitude thruster that your ship uses. This fuel injector has worn thin over years of misuse and causes pressure issues, which make coffee leak out of every seam. If the players choose to sacrifice an RCS thruster or a spare part, they can fix the coffee machine with little issue.

Without our Heroes' Help... Noru tries to fix the machine during the graveyard shift when nobody is watching. Unfortunately, these attempts do not work. When Dusty (or Rusty) wakes up early and goes to brew a cup, he finds them there. They are accused of returning to the scene of the crime, and Dusty and Rusty once again unify against the person they believe is responsible.

Fights about the espresso machine will underscore more important conflicts between workers.

The coffee machine will remain forever broken. Tensions will remain high. Eventually, it will be deemed totally dead and hoisted off the Mother and onto the cold, uncaring surface of Mercury.

A Sojourner in a Foreign Land

A small meteorite has landed outside after passing a remarkably low perihelion close to the sun's surface - externally, it appears to be a chunk of ice - of a size and mass that should not have survived its trajectory this close to the sun. Is it an opportunity to obtain a rare mineral? A sign of frozen extrasolar life (even evidence of panspermia)? An unknown-but-deadly weapons system from one of humanity's own planets?

How to Introduce Both the ship's and the Mother's radar and telescope systems notice an object on a ballistic toward the surface. Any investigation reveals that it will not impact the Mother or any infrastructure. Its albedo and radar cross section suggest it is somewhat small - between 10 cm and 1 meter.

It Develops... Analysis of the trajectory shows it passed by Earth some time ago, but that it originated from further out - the far reaches of the solar system, even the Oort Cloud.

The players find a Pallasite Meteorite - a chunk of stony iron with olivine crystals. If a player character knows about geology, they would know that the outer mantle of Earth is primarily olivine, but that's not evidence it came from Earth. An Orphan fragment hit earth in 2137, but the debris it kicked up were not very energetic, at least not energetic enough to enter solar orbit.

The sample is consistent with Orphan event debris. It may have separated at the original Orphan Event.

Without our Heroes' Help... Nothing happens. The rock is forgotten, but the record of the event is recorded in some crew logs.

Important NPCs

Grip Torsion *he/him* (Station Foreman) Respected for his unwavering commitment to the Hermes mission, he harbors an almost fanatical obsession with maintaining every iota of energy output from the Swarm in order to power the rest of the solar system. However, he also holds a deep secret: in a prior role as a department supervisor, his devotion to this energy output above all else directly caused the death of one of his team and the serious injury of another. The accident was blamed on equipment failure, and the only other person who knows the truth is Mya Jensen, who Torson has bribed to keep the accident a secret.

Rusty and Dusty *he/they and she/her* (Maintenance Engineers) Rusty is a lanky young man with curly red hair (which is presumably where he got his name). Dusty is a gruff, stocky woman in her 40s whose face is perpetually covered in some sort of grime but whose overalls are somehow always relatively spotless. Between the two of them, they know essentially everything mechanical that goes on in The Mother. And it is truly between the two of them - no one is quite sure where Rusty's knowledge ends and Dusty's begins. If you report a problem to Dusty, it is not unlikely that Rusty will be across the station patching it up within minutes, without ever having apparently talked to Dusty.

Rusty usually carries duct tape, and Dusty usually carries canned grease. Together, they keep moving things moving and stationary things stationary.

Nyles Miller *he/him* (Staff supervisor, main Lancer Corporation conspirator on The Mother) Miller is outwardly an affable man who occasionally disagrees with Torson on priorities for The Mother – as the man in charge of taking care of the workers, he tends to be more skeptical of Torson's prioritization of the Swarm's energy output. However, he has worked his way up to this position while under cover, telling nobody of his conflicting offworld connections.

Mya Jensen *she/they* (Production engineer, reluctant Lancer Corporation conspirator on The Mother) A small wiry woman with shaggy shoulder-length brown hair, Jensen works in drone production. She has a detailed knowledge of the technical aspects of the Swarm's operations, which comes in handy for her true employers at the Lancer Corporation who are looking for ways to take over those operations. Her knowledge of Torson's secret has motivated her to seek a change in leadership by any means necessary, but she is becoming more and more aware of how many more lives the Lancer Corporation will brush under the rug to clear the way towards their goal.

Minor NPCs

Noru *they/them* With a round face and straight black hair that is haphazardly chopped off in a variety of…creative styles, Noru is the smallest adult you have seen on The Mother, if indeed they are 21 as they claim. You have never seen or heard from Noru unless they were in some sort of trouble, usually of their own making. Still, they always have their finger on the pulse and love to keep you updated on the station's drama.

Becca Hemley *she/her* The living quarters of the Hemley family are so cozy you could almost trick yourself into thinking that you're still on a planet that humans were meant to live on. Becca is always eager to host friends and travelers, and loves to hear stories from across the solar system while her kids run underfoot and occasionally pop up to ask whether space ships really burn the crew's poo to get a "turboboost".

Old Sly *he/him* Sly is technically not too old to work, but nobody can really keep him sober enough to do any job safely. Instead he walks along with other crews, occasionally doing piecework or rides along on supply runs, always telling tall tales about his previous years on the station. The Mother occasionally gets shipments of actual alcohol, but Sly thinks rocket ethanol is fine if diluted enough. His fellow crew members would die for him.

Lena Bersch *she/her* A brusque blonde woman in her thirties, Bersh runs the signals lab on the Mother. It wasn't exactly given the most robust sensor array, but she works wonders with what she's got. Her team monitors the Swarm, keeps an eye on the sun, and occasionally catches a stray signal or radar reading from the solar system if it is enough of an irregularity.

2 Venus

A hot, high-pressure planet whose habitable zone is a thin shell in the upper atmosphere.

Orbital Parameters

Semi-Major Axis	$1.08210 \times 10^8 km$
Eccentricity	0.00678
Argument of Periapsis	54.9°
Longitude of Ascending Node	76.78°
Mean Anomaly at Epoch	50.115°
Inclination	3.3957°

Other Parameters

Gravity Factor	3.249×10^{14}
Mass	$4.8673 \times 10^{24} kg$
Axial Tilt	177.26°
Synodic (solar) Day	116.75 days (retrograde)
Sidereal Day	243.0226 days (retrograde)
Sidereal Orbital Period	224.7 days
Surface Gravity	$8.87 m/s^2 (0.902 g)$
Gravity (Habitats)	$8.73 m/s^2 (0.890 g)$
Escape Velocity	10.36 km/s
Equatorial rotation velocity	1.81 m/s (6.52 km/h)
Blackbody Temperature	226.6 K (0 C)
Radius	6051.8 km
Surface Temperature	737k (464 C)
Surface Pressure	92 bar
Surface Wind Speeds	$0.3 \rightarrow 1.0$ m/s

Atmospheric Composition

Carbon Dioxide (CO_2)	96.5%
Nitrogen (N_2)	3.5%
Sulfur Dioxide (SO_2)	150 ppm
Argon (Ar)	70 ppm
Water (H_2O)	20 ppm
Carbon Monoxide (CO)	17 ppm
Helium (He)	12 ppm
Neon (Ne)	7 ppm

[1] [2] [3]

Common Knowledge

A terrestrial planet with a thick, dense atmosphere. Clouds completely obscure the surface from orbit. A runaway greenhouse effect has heated the planet to more than 700 kelvins. Long thought to be Earth's twin, colonization of Venus has proven difficult, with humans surviving in flying cities that float high in its soupy atmosphere, fifty kilometers above the ground. Structures for living are suspended from torus balloons of hydrogen, and life is very similar to that of life in space stations, though with near-Earth gravity. Air is still too toxic to breathe, but temperatures in this region are easy to regulate, being between 20 and 75 C, and atmospheric pressure is similar to Earth.

The troposphere, the lowest part of the atmosphere, super-rotates, pushing clouds as quickly as 100 meters per second.

Additional breathing air is kept in auxiliary balloons – the oxygen/nitrogen mixture is buoyant in the carbon-dioxide environment. The atmosphere that remains above protects from most cosmic radiation. These floating colonies are hard to access from orbit, and specialized shuttles are needed to make human and cargo transport possible, hovering beneath the habitats and hooking a cable from beneath, to avoid exhaust damaging the city.

Though life is cramped and fresh air is rare, the danger on Venus is minimal. Only rarely has a city's safety measures failed to prevent disaster, leaving a colony to plunge below the clouds into the lethal pressure ocean below.

Venus' surface is dotted with volcanoes, which spew magma onto its mosaic of basalt plains. What appear to be rivers from radar are really cooled flows of igneous rock. These gorgeous views are entirely obscured by the thick cloud layers of sulfuric acid.

[1] At CO_2 levels above 1%, a heightened heart rate is typical. At levels above 10%, most people experience convulsions, coma, and death. At 30% or greater, loss of conciousness occurs in seconds.

[2] At around 150 ppm, the sulfur dioxide is lethal at 5 hours. Exposure should be limited to 30 minutes.

[3] At 17 ppm, the carbon monoxide is not lethal but impairs performance.

Locations

Three companies have set up stations and dominated the settlement of Venus. These are:

White Whale Station - Minnow Industries Todd Mayhew, the executive at Minnow that spearheaded their decision to build on Venus, is very proud of himself for coming up with such a metaphorical name for the station that contrasts with the name of the company. White Whale Station, like the other two stations on Venus, has a dual purpose of mining deuterium and housing a resort that is tailored to luxurious tastes. White Whale is a popular spot for upper class socialites and some power brokers – many well-known business leaders and politicians go here when they can get away, or send their families if they need a break from them. The resort boasts occasional glimpses of marble or gilded accents in decor, but more often has sophisticated plastics and other simulations of such materials, the real deal being prohibitively heavy for a floating station. The mining operations here are somewhat neglected, but the workers are still expected to consistently produce quality deuterium fuel, leading to a persistent friction that management desperately tries to keep away from the resort.

Divitem Caelos - Quorum Interplanetary What is usually referred to as DC is, somewhat ironically, not where politicians or power brokers hang out on Venus. This is where the people who are beyond brokering their power retreat to. Those who control global hedge funds from behind the scenes, who hold near-total monopolies on industries that no one thought to pay attention to, who can say a word that makes its way into a president's ear as an order. These people rarely feel the need to risk their lives in space travel, so DC is usually full of stuffed suits that are the most secretive of messengers and smooth negotiators on behalf of their superiors. The amenities here are spartan and functional. The mine operations are largely to create as much self-sufficiency on the station as possible, and are for the most part not on a true industrial scale. While this lessens their dependency on the outside world to some degree, it also increases their dependency on their own systems – if anything happens to the mining operation, it could jeopardize the safety and security of the cabal-like activities of the rest of the station.

Cloud 69 - Magnus, Inc. There are some cultures that, however widely detested, manage to hang on and even grow and spread to places that don't seem hospitable to them. Among those is the chokingly toxic ego-centric culture constructed by Silicon Valley frat bros, the type that thinks taking a pedestrian joke and slapping it onto the front of a historic interplanetary effort is a sign of subversiveness and shrewd wit. Thus Richard Magnus took a large portion of the resources of the corporation run by his father, got together with some of his college buddies, and convinced planetary speculator and developer Benny Huff to let him build the third station on Venus. Since Magnus and his friends knew very little about the floating resort/mine business, Huff accepted a hefty commission fee to provide them with some cookie-cutter guidelines

– mostly lifted from the two other stations that Huff brought to the planet. Magnus and his friends took little trouble to add on to the designs (often doing the opposite and stripping down things they thought were unnecessary or looked too pretentious), and the result was a station that managed to beat out DC for blandness. Their attempts to draw in visitors by advertising cheaper, rules-light space vacations occasionally worked, but their ineptitude at running the mines soon led to the miners asserting their knowledge and experience and more or less running the mines on their own terms.

First Sight

On first approach, the dusky orange-brown of Earth's less-hospitable twin looks deceptively enticing, perhaps like the god of love she was named for. The light streaming through her atmosphere is initially reminiscent of a sandy sunset, but as you draw closer you can make out individual cloud formations, the gaseous layers of the atmosphere that outline the different levels of deadliness Venus has to offer. The color grows more sickly, and therefore more true to its nature. As you dive through the exosphere, the station comes into sight. If you did not have this shelter to look forward to, even the strongest and most specialized of shields on your ship would not save you from the eventual corrosion that would eat up your ship as you fell through this most hostile of the terrestrial atmospheres, before being crushed by an ever-thickening sea.

Congratulations on making it to Venus. Now all you have to worry about is dealing with the kinds of people who would voluntarily live here.

Plots

It Starts With One - White Whale

As with most space employment contracts, it's hard to get fired on Venus. The massive cost of sending you home early means that employers screen heavily and are reluctant to fire workers for tardiness, unprofessionalism, or other minor issues. Sabotage is not one of those minor issues, though, and this is what Byron Wright is being accused of. The White Whale station on Venus, run by Minnow Industries, is in an uproar after several services have ground to a halt due to Wright's actions. However, he protests that he is not to blame; rather, Minnow refuses to adequately pay its workers and maintain its equipment, and he is only encouraging others to bring these issues to light.

How to Introduce Players encounter multiple delays and other indications of issues with services like transport, food, or sanitation. If they talk to someone in the working class, these may be explained as failures on Minnow's part to invest properly in maintenance and ongoing services. If they talk to someone aligned with Minnow, or a worker who has not been convinced by Wright's faction, these may be blamed on worker dissatisfaction or laziness.

If they express interest in helping, the worker they talk to is only a few degrees of separation from Wright. If they do not immediately pursue the lead, Wright is coincidentally involved in a demonstration near one of their next stops, and eagerly approaches them as outsiders to recruit to his cause.

It Develops... Players soon realize that the disturbances stem from Wright's realization of how much workers on the station do beyond the contracted work they signed up for. Transit drivers have had to learn to maintain their vehicles; cooks are forced to handle logistics for cafeterias and even serve the food when they are understaffed; sanitation workers are driving, picking up trash, and self-coordinating the disposal of waste without proper facilities or direction. Wright and his team have convinced many of these workers to simply stop doing this extra work and perform only the work outlined in their original contracts. His (slightly self-important) exhortation has been to "stop doing things the wrong way - do them the Wright way!"

Minnow has worked to crack down on these workers, rather than hiring new hands or properly supplying the current workers. White Whale station manager Dren Howe soon pulls Wright from his job duties as a janitor and shuts down his access to any company systems or resources. Wright is punished as much as possible short of sending him home, and Howe threatens to do this, too; however, all of this only gives him more time to organize.

Howe works to mitigate issues for habitat maintenance engineers and other teams that Wright has not yet influenced, in an attempt to weaken Wright's arguments and prevent the spread of the work protests. Howe reaches out to players for resources, influence, and assistance with a few repair issues around the station in order to lighten the load without acquiescing to Wright's demands.

This is a rather open-ended situation - it is up to the players to attempt to create a solution that brings these two vastly differing sides closer together, or do what they can to ensure the success of one or the other.

Without our Heroes' Help... Wright's actions grow more dangerous, and Howe and other Minnow officers do not hesitate to respond swiftly, sanctioning anyone associated with the movement and imprisoning Wright until he can be returned to Earth. Wright's supporters have become fewer with his drastic actions, but they stage a protest that threatens to ground one of the major support hubs for the station (being "grounded" on Venus is a rather unfortunate fate). The protest, with little support from the larger working class, is crushed by Minnow security.

Down in the Mines - Divitem Caelos

Venus in its natural state is not a friendly place, so all mining operations are essentially automated, save for some of the guidance and maintenance that is done from the headquarters in the clouds. However, equipment breaks down frequently and that maintenance is no light work, especially given how little management wants to spend on upkeep. The maintenance crews are a tight-knit community, which makes the two unexplained deaths among them even stranger. A repairman named Kash Vytall and a supervisor named Naria Holt have met sudden, violent ends, by means that could ostensibly be explained as workplace accidents if they weren't so concurrent. The other crew members are offering little help to investigators beyond a few details that sound rehearsed. If these were accidents, why aren't other maintenance crew pushing for more safety measures? If these were murders, why aren't they trying to find the threat?

How to Introduce The characters hear about two sudden, shocking deaths by word of mouth or through some news cycle. It is a hot piece of news, and given the surrounding mystery, it continues to pop up as various theories are propagated and then tossed aside. A higher up in Divitem Caelos (DC) may mention that it is a mystery that needs solved in order to close the corporate case file. If players can do that, they may be owed a favor by someone who can pull serious strings on Venus (or possibly a payout, if the bigwig can get it approved).

It Develops... Players can go around asking questions, but will likely get the same stonewall that other investigators have. They will need to establish trust with the community of maintenance crew and their families - this could happen any number of ways, but a perfect example would be the acceptance of a small superstition without hesitation. After all, that is what this is all about…

With enough trust, enough reassurances, however the GM wants to play it, the community (or at least one of them) confides in the players: There is a hatch on the bottom layer that, more or less, leads out into the open Venusian sky. It is hidden behind a corner and has never really been used. At some point in the past few years, an old woman named Buddy left a broken tool near the opening and forgot about it overnight. When she went back the next morning, it was quite literally as good as new. This happened a few more times with Buddy, who was more than glad that at least somebody or something was making the repairs that management never seemed to see as a problem. Buddy kept this a secret until she was on her deathbed, where she told her nephew about the seemingly magic hatch. But, as the nephew Jud tells it, she gave an ominous warning as well: "Never look…in the mouth" Since then, several people have testified to direct miraculous experience with the hatch, but they always back up to it when they are dropping off or picking up tools or equipment. They never look into it.

Anyway, Kash Vytall didn't see the need for this secrecy and decided to tell a supervisor about the hatch so they could look into it and better utilize it. The community is extremely protective of it, however, and has the "if we mess with it it will stop working" mindset to a fanatical degree. When others found out that he and Naria Holt both knew about it, and intended to spread the news all over, they took drastic action to protect the secrecy of the one bit of help that didn't come by corporate half-measures.

That they shared this secret with the players is an unlikely turn of events, and perhaps doesn't bode well for their future, either… but it all depends on what they do with the community's trust. If players were to openly side with the workers in stonewalling the investigation, losing the favor from DC officials would be only the beginning of their troubles. If they betray the trust of whomever revealed the secret, things could get even bloodier in the community - especially for the players.

Without our Heroes' Help... The rewards offered for more information eventually prove too enticing, and someone anonymously tips the officials to someone involved in the deaths, though not to the reason why. This person is executed, and this unknown leak starts to poison the worker's relationships with each other with suspicion. With this divisiveness, the bosses are more able to exploit the workers than ever before.

Divitem Caelos

As effective as deuterium can be as a fuel, it still can only come second to the essentially free option of Hermian energy. Research is constantly being done to find new uses and new processes for the Venusian export in order to increase its appeal, and it seems that someone on DC may have just made a breakthrough.

One of the reasons that space is not even more dangerous is the lack of weaponry. Leaving aside the difficulty of adapting terrestrial personal firearms to use in space environments without destroying the habitat of the weapon's user, on a larger scale, any missile with a viable payload is easily detectable and shot down. Modern-day sensors are finely tuned to pick up any combustible materials; there is almost no interplanetary use for such volatile compounds anymore, so their presence would be suspicious. Deuterium did not register as a danger - until now.

Deuterium has long been accepted as a fuel without being seen as particularly dangerous, due to the specialized process needed to burn it for fuel. Creating a system to burn a large amount at once is more or less logistically impossible. But this breakthrough unlocked a method to initiate a chain reaction, and now missiles could be disguised as ships with deuterium engines and approach unsuspecting targets to detonate their payloads at close range.

How to Introduce Players are contacted with a contract to carry special cargo back to Earth. There is a strict no-questions-asked policy which, though fairly common in places like the Belt, is somewhat unusual in this area. This cargo contains the first prototype of the reactor system as well as the reluctant scientist and equipment that made it.

It Develops... The players may investigate and discover some of the true nature of the cargo, or they may discover that they are being contracted by the owners of DC, which might raise some red flags. Wherever they are told to go on Earth also seems sketchy, since the owners are trying to keep this away from literally everyone, including all governments. With any prodding or encouragement, the scientist likely spills the beans and/or tries to destroy his discovery and get away. He knows the full weight of what he created. The DC owners are tracking the players, either openly or secretly, to make sure their precious cargo reaches Earth.

It becomes obvious that these owners needed to contract an independent ship because the cargo needs to go now, and any unscheduled official DC shipping could garner attention. This does mean that, as far as we know, nobody in the system could replicate this fuel system without what is on this ship. However, DC will hunt the players down and probably kill them if they simply up and run.

Without our Heroes' Help... DC ends up getting the cargo to Earth another way, probably resorting to a company ship. Though they make it to Earth, they do not successfully fly under the radar of the authorities. At least one government investigates and becomes privy to the secret that deuterium can be weaponized. This secret is all the more dangerous because no one else in the system knows about it, and will be unsuspecting of deuterium signatures on their sensors. No one knows what the future could hold, but if that government still holds a grudge against the Hermians or anyone else, bad things could happen.

A Titanic Expedition - Cloud 69

One wealthy member of the Magnus family, Richard, wants to make the first human expedition to the surface of Venus - despite its 475 degree C temperature and 93 bar atmospheric pressure. Ignoring the safety concerns of every reputable scientist and engineer, Richard has fashioned a vessel of his own design to reach the surface and is already selling tickets for the first expedition. Venusian locals tend to not be that well-versed in science and several celebrities have already announced their plans to take a trip to the surface. Can you convince the Venusians of the danger?

How to Introduce

It Develops...

Without our Heroes' Help...

How to Introduce

It Develops...

Without our Heroes' Help...

Chapter 3

GM Resources

1 Running the Game (GM)

TODO: Write GM guide

1.1 Campaign Styles

Different campaigns have different styles and tones. The following sections describe different ways to run your campaign. These are not mutually exclusive, or set in stone. You can pick aspects of each à la carte. These are provided only for guidance and inspiration.

One-Shot

Westmarches Style

Episodic

Serial

A modern style of TTRPG campaigns...

1.2 Building the World

TODO: Write Worldbuilding guide

Planet of Hats

Chapter 4

Physics

1 Mathematics

Here are important mathematical definitions and identities. This book is not intended to teach these concepts, but rather provide review and quick reference during calculation.

1.1 Scalars

Scalars are quantities without a direction. Scalars are denoted with a singular letter, e.g. v, a.

1.2 Vectors

Vectors are commonly defined as values that have both direction and magnitude; they contain values that cannot be expressed as a single number (a scalar). Vectors can be stored as a *magnitude* and set of angles, or as tuples of Euclidean components. For example, a vector $\vec{v}$ (indicated by an arrow here) is notated as

$$\vec{v} = \begin{bmatrix} v_1 \\ v_2 \\ \dots \\ v_n \end{bmatrix} \tag{4.1}$$

Cartesian vectors

In Exotic Matters, all vectors are 3-vectors. Cartesian vectors describe three components, on x, y, and z axes. For example, radius vector $\vec{r}$, from the center of a planet to the center of a spaceship, is:

$$\vec{r} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x \; y \; z \end{bmatrix} \tag{4.2}$$

Unit Vector

Unit vectors are special vectors, 1 unit long, along the axes. These vectors are defined as:

$$\begin{aligned} \hat{x} &= \begin{bmatrix} 1 \; 0 \; 0 \end{bmatrix} \\ \hat{y} &= \begin{bmatrix} 0 \; 1 \; 0 \end{bmatrix} \\ \hat{z} &= \begin{bmatrix} 0 \; 0 \; 1 \end{bmatrix} \end{aligned}$$

Vectors can be described as complex number along unit vectors: $a\hat{x}+b\hat{y}+c\hat{z}$ (e.g. $26.2\hat{x} + -36.1\hat{y} + 1.2\hat{z}$). This helps contextualize them to a particular coordinate system.

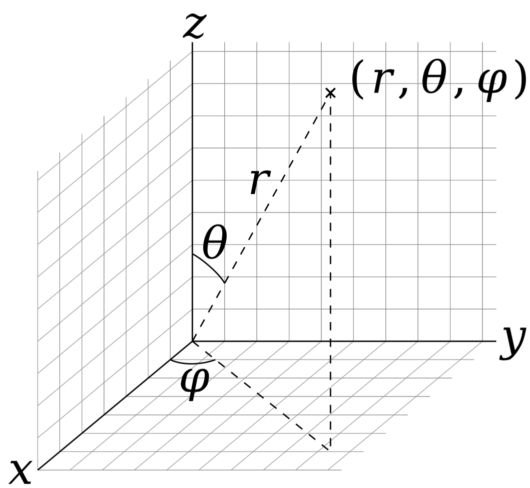


Figure 4.1: Spherical coordinates using Physics conventions.

A vector in the form of $a\hat{x} + b\hat{y} + c\hat{z}$ is identical to the two matrices:

$$\vec{v} = \begin{bmatrix} \hat{x} & \hat{y} & \hat{z} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{4.3}$$

Spherical Coordinates

Vectors may also be given in spherical coordinates, with r, θ and φ components. The convention used in this book is the one commonly used in physics: r represents the magnitude (length) of the vector. θ represents the angle from the polar axis $\vec{z}$, also called **zenith angle**. The reciprocal of this, **inclination**, also known as *elevation*, is measured upward from the horizon or fundamental plane. φ represents the angle of rotation from $\vec{x}$ in the counter-clockwise direction. φ is also called **azimuth** or *azimuthal angle*. Figure 4.1 shows these measures in relation to the Cartesian axes.

It may be helpful to chant "R Theta Phi" several times to remember the order of these components.

Like Cartesian vectors, spherical vectors can be notated as a complex number with three components: $a\hat{r} + b\hat{\theta} + c\hat{\varphi}$.

Converting between Cartesian and spherical

Spherical to Cartesian:

$$x = r\ sin\,\theta\ cos\,\varphi$$
$$y = r\ sin\,\theta\ sin\,\varphi$$
$$z = r\ cos\,\theta$$

Cartesian to Spherical:

$$r = \sqrt{x^2 + y^2 + z^2}$$
$$\theta = tan^{-1}\left(\frac{\sqrt{x^2 + +y^2}}{z}\right)$$
$$\varphi = tan^{-1}\left(\frac{y}{x}\right)$$

Vector Addition and Subtraction

To add two vectors, simply add each of their components:

$$\vec{a}+\vec{b}=\begin{bmatrix}x_a\\y_a\\z_a\end{bmatrix}+\begin{bmatrix}x_b\\y_b\\z_b\end{bmatrix}=\begin{bmatrix}x_a+x_b\\y_a+y_b\\z_a+z_b\end{bmatrix}$$

Note that vector addition is commutative: $\vec{a}+\vec{b}=\vec{b}+\vec{a}$. Addition is also associative: $\vec{a}+(\vec{b}+\vec{c})=(\vec{a}+\vec{b})=\vec{c}$

Subtraction, likewise, is done per-component.

$$\vec{a}-\vec{b}=\begin{bmatrix}x_a\\y_a\\z_a\end{bmatrix}-\begin{bmatrix}x_b\\y_b\\z_b\end{bmatrix}=\begin{bmatrix}x_a-x_b\\y_a-y_b\\z_a-z_b\end{bmatrix}$$

Unlike addition, it is not commutative: $\vec{a}-\vec{b}\neq\vec{b}-\vec{a}$.

Additionally, the opposite of a vector $-\vec{v}$ is a vector with each component the opposite:

$$-\vec{v}=-\begin{bmatrix}x\\y\\z\end{bmatrix}=\begin{bmatrix}-x\\-y\\-z\end{bmatrix}$$

This effectively reverses its direction while keeping its magnitude.

Adding and subtracting vectors in spherical coordinates is essentially paramount to converting them to Cartesian form before adding.

Vector Magnitude

Magnitude is the length of a vector. It is given by the Euclidean distance formula, and notated using absolute value bars, or the same variable without the arrow:

$$||\vec{v}||=v=\sqrt{x^2+y^2+z^2}=r$$

Normalized Vectors

The normalized vector of a vector is another vector in the same direction as the original, but only one unit long. It is notated with a hat, like a unit vector: $\hat{v}$. To get the normalized vector of a given vector, divide each component by the magnitude:

$$\hat{v}=\frac{\vec{v}}{v}=\begin{bmatrix}\frac{x}{v} & \frac{y}{v} & \frac{z}{v}\end{bmatrix}=\begin{bmatrix}1\,\theta\,\varphi\end{bmatrix}$$

Zero Vector

The zero vector $\vec{0}$ has no direction or magnitude and all three components equal to zero.

There are a few notable properties of the zero-vector:

$$
\begin{aligned}
\vec{a} + \vec{0} &= \vec{a} \\
\vec{a} - \vec{0} &= \vec{a} \\
\vec{0} - \vec{a} &= -\vec{a} \\
\vec{a} + (-\vec{a}) &= \vec{0} \\
0 \cdot \vec{a} &= \vec{0}
\end{aligned}
$$

Finally, $0 \neq \vec{0}$. The two are different types.

Multiplying Vectors by Scalars

Multiplication of a vector by a scalar is straightforward. The direction remains unchanged but the magnitude is multiplied by the scalar. Think of this as stretching the vector (if the factor is > 1) or squashing the vector (if the factor is < 1).

Multiply each element of the vector by the scalar.

$$
a \cdot \vec{b} = \begin{bmatrix} a \cdot v_1 \\ a \cdot v_2 \\ \cdots \\ a \cdot v_n \end{bmatrix}
$$

As division is the reciprocal of multiplication, vectors may be divided by scalars (but not vice versa). Addition and subtraction cannot be done between a scalar and a vector.

Other properties of vector-scalar multiplication:

$$
\begin{aligned}
a(b\vec{c}) &= (ab) \cdot \vec{c} && \text{associativity} \\
(a+b)\vec{c} &= a\vec{c} + b\vec{c} \\
a(\vec{b} + \vec{c}) &= a\vec{b} + a\vec{c} \\
1 \cdot \vec{a} &= \vec{a} \\
0 \cdot \vec{a} &= \vec{0} && \text{The zero-vector (see sec. 1.2)}
\end{aligned}
$$

Multiplying Vectors by Vectors

There are two types of multiplication for vectors, and it is important to know the difference. The first is the dot product, denoted by the symbol $\cdot$ and the second is the cross product, denoted by the symbol $\times$.

Vector Dot Product

First the dot product:

$$\vec{a} \cdot \vec{b} = x_a x_b + y_a y_b + z_a z_b = a\,b\,cos\,\theta$$

where θ is the angle between the two vectors. The dot product turns two vectors into a scalar value. Remember that $|\vec{a}| = a$. The result of a dot product is a scalar.

Consider the dot product as a measure of similarity between two vectors; notice how the angles $\theta = 0$, $\theta = \frac{\pi}{2}$, and $\theta = 2\pi$ affect the dot product: they stretch the product by a factor of 1, 0, and -1 respectively.

$$\vec{a} \cdot \vec{b} = 0 \implies \vec{a} \perp \vec{b}$$

Some interesting properties of the dot product include:

$$\begin{aligned}
\vec{a} \cdot (\vec{b} + \vec{c}) &= \vec{a} \cdot \vec{b} + \vec{a} \cdot \vec{c} && \text{(Associative Property (Vector))}\\
(c\vec{a}) \cdot \vec{b} &= \vec{a} \cdot (c\vec{b}) = c(\vec{a} \cdot \vec{b}) && \text{(Associative Property (Scalar))}\\
\vec{a} \cdot (b\,\vec{c}) &= b\,\vec{a} \cdot \vec{c} &&\\
\vec{a} \cdot \vec{a} &= ||\vec{a}||^2 = a && \text{(Because } sin(0) = 1\text{)}\\
\vec{a} \cdot \vec{0} &= 0 && \text{Multiplication by zero-vector}\\
\vec{a} \cdot \vec{b} &= \vec{b} \cdot \vec{a} && \text{(Transitive Property)}\\
\vec{a} \cdot \vec{a} &= 0 \implies \vec{a} = \vec{0} &&\\
\vec{a} \cdot \vec{b} &= a \cdot b && (4.4)
\end{aligned}$$

Vector Cross Product

The cross product, on the other hand, is a vector value normal (perpendicular) to the plane created by two vectors. Consider that a 2-D plane can be defined by three points in 3-space. Two vectors with coincident origins share the first point, making their ends the second and third points, thus defining a shared plane. Similar to the dot product, the magnitude of the cross product gives some information about their similarity. Unlike the dot product, the cross product produces a vector pointing out of the plane positively or negatively to express that similarity.

The definition of the cross product is:

$$\vec{a} \times \vec{b} = \begin{bmatrix} x_a \\ y_a \\ z_a \end{bmatrix} \times \begin{bmatrix} x_b \\ y_b \\ z_b \end{bmatrix} = \begin{bmatrix} y_a\,z_b - z_a\,y_b \\ z_a\,x_b - x_a\,z_b \\ x_a\,y_b - y_a\,x_b \end{bmatrix} = a\,b\,sin(\theta)\vec{n} \tag{4.5}$$

where θ is the angle between the two vectors on the plane containing them[1] and where $\vec{n}$ is the unit vector perpendicular to the plane containing them, with direction that makes the ordered set (a, b, n) positively oriented[2].

The magnitude of the cross product is equal to the area of the parallelogram with $\vec{a}$ and $\vec{b}$ as its two defining sides ($||\vec{a} \times \vec{b}|| = Area$).

The cross product is not commutative ($\vec{a}\times\vec{b} \neq \vec{b}\times\vec{a}$), but it is *anticommutative* ($\vec{a} \times \vec{b} = -\vec{b} \times \vec{a}$).

Compare the cross and dot products' definitions.

Properties of the cross product:

$$\vec{a} \times \vec{a} = \vec{0} \qquad \text{(Zero-vector)}$$

$$(a\,\vec{b}) \times \vec{c} = a(\vec{b} \times \vec{c}) \qquad \text{(Associativity)}$$

$$\vec{a} \times \vec{b} = -\vec{b} \times \vec{a} \qquad \text{(Anticommutivity)}$$

Less important properties of the cross product:

$$\vec{a} \times (\vec{b} \times \vec{c}) = \vec{b} \cdot (\vec{c} \times \vec{a}) = \vec{c} \cdot (\vec{c} \times \vec{a})$$

$$\vec{a} \times (\vec{b} \times \vec{c}) = (\vec{a} \cdot \vec{c})\,\vec{b} - (\vec{a} \cdot \vec{b})\,\vec{c} \qquad \text{Triple cross product}$$

$$(\vec{a} \times \vec{b}) \cdot (\vec{c} \times \vec{d}) = (\vec{a} \cdot \vec{c}) \cdot (\vec{b} \cdot \vec{d}) - (\vec{a} \cdot \vec{d}) \cdot (\vec{b} \cdot \vec{c})$$

Vector Functions

Functions can take vectors as arguments and return vectors. A vector function, such as $\vec{f}$, will be given an arrow like a vector value. Vector functions can also be derived: $\frac{d\vec{r}}{dt}\vec{r} = \dot{\vec{r}}$ and $\frac{d^2\vec{r}}{dt^2}\vec{r} = \ddot{\vec{r}}$.

1.3 Matrices

A matrix is an arrangement of scalars in both rows and columns. In this book, matrices are denoted in bold with an underline ($\underline{\mathbf{A}}$).

$$\underline{A} = \begin{bmatrix} 1 & 2 & 3 \\ a & b & c \end{bmatrix} \tag{4.6}$$

1.4 Reference Frames

There is no global static origin against which the universe may be measured. All measurements must be done against some other point: the origin. Additionally, if a direction is to be measured, it must be measured against another known direction.

[1] Usually the orbital plane or reference plane for our purposes.

[2] The right-hand rule; $\vec{a}$ is index finger, $\vec{b}$ is middle finger, and $\vec{n}$ is thumb

For this reason, three **unit vectors** (see section 1.2) define the axes of a reference frame.

Reference frames will be notated using a calligraphic F ($\mathcal{F}$) accompanied by a subscript (e.g. $\mathcal{F}_S$, $\mathcal{F}_B$).

All unit vectors must be orthogonal to each other (i.e. each at right angles to each other). Unit vectors are called $\hat{x_n}$, $\hat{y_n}$, and $\hat{z_n}$, where n is the name of the reference frame (e.g. $\mathcal{F}_S$ has unit vectors $\hat{x_S}$, $\hat{y_S}$, and $\hat{z_S}$). The number of dimensions refers to the minimum number of axes required to uniquely describe a point in space. In three-dimensional space, a reference frame will by definition have three unit vectors.

By definition, the following must be true:

$$\hat{x_n} \times \hat{y_n} = \hat{z_n}$$
$$\hat{y_n} \times \hat{z_n} = \hat{x_n}$$
$$\hat{y_n} \times \hat{x_n} = \hat{z_n}$$

Also, Multiple reference frames can exist at the same point, oriented in different ways. The direction of one fundamental axis (the x-axis) will give rise to all axes via the right-hand rule.

Inertial Reference Frames

An **inertial reference frame** is a non-rotating frame of locally flat space that is not experiencing any acceleration. In such a frame, an isolated physical object that is experiencing no force will maintain a constant velocity.

Vectors in Reference Frames

Consider the reference frames $\mathcal{F}_a$ and $\mathcal{F}_b$. Now consider a vector c:

$$\vec{c} = c_{x,a}\hat{x_a} + c_{y,a}\hat{y_a} + c_{z,a}\hat{z_a} \tag{4.7}$$

This vector has three scalar components, which are measured in $\mathcal{F}_a$. Remember that any vector can be represented as two multiplied matrices:

$$\vec{c} = \begin{bmatrix} \hat{x_a} & \hat{y_a} & \hat{z_a} \end{bmatrix} \begin{bmatrix} c_{x,a} \\ c_{y,a} \\ c_{z,a} \end{bmatrix} \tag{4.8}$$

Now, we take the magnitudes as measured in this reference frame as its own matrix:

$$\underline{\mathbf{c_a}} = \begin{bmatrix} c_{x,a} \\ c_{y,a} \\ c_{z,a} \end{bmatrix} \tag{4.9}$$

$\underline{\mathbf{c_a}}$ means *the scalar components of $\vec{c}$ in $\mathcal{F}_a$*. We can substitute this concise symbol back into 4.8:

$$\vec{c} = \begin{bmatrix} \hat{x_a} & \hat{y_a} & \hat{z_a} \end{bmatrix} \underline{\mathbf{c_a}} \tag{4.10}$$

We can also give the reference frame a symbol (though, in column-matrix form for reasons made obvious soon):

$$\vec{\mathcal{F}_a} = \begin{bmatrix} \hat{x_a} \\ \hat{y_a} \\ \hat{z_a} \end{bmatrix} \tag{4.11}$$

And so, we can make the matrix definition even more concise[3]:

$$\begin{aligned} \vec{c} &= \vec{\mathcal{F}_a}^T \underline{\mathbf{c_a}} \\ &= \underline{\mathbf{c_a}}^T \vec{\mathcal{F}_a} \end{aligned} \tag{4.12}$$

Any vector can be written as their set of components as seen from a particular reference frame. This form is called the **vectrix**.

Translation Between Reference Frames

Recover the directional components from the vectrix.

$$\begin{aligned} \vec{c} &= \vec{\mathcal{F}_a}^T \underline{\mathbf{c_a}} && \text{from 4.12} \\ \vec{\mathcal{F}_a} \cdot \vec{c} &= \vec{\mathcal{F}_a} \cdot (\vec{\mathcal{F}_a}^T \underline{\mathbf{c_a}}) && (4.13) \end{aligned}$$

We then turn aside to solve $\vec{\mathcal{F}_a} \cdot \vec{\mathcal{F}_a}^T$:

$$\begin{aligned} \vec{\mathcal{F}_a} \cdot \vec{\mathcal{F}_a}^T &= \begin{bmatrix} \hat{x_a} & \hat{y_a} & \hat{z_a} \end{bmatrix} \begin{bmatrix} \hat{x_a} \\ \hat{y_a} \\ \hat{z_a} \end{bmatrix} \\ &= \begin{bmatrix} \hat{x_a} \cdot \hat{x_a} & \hat{x_a} \cdot \hat{y_a} & \hat{x_a} \cdot \hat{z_a} \\ \hat{y_a} \cdot \hat{x_a} & \hat{y_a} \cdot \hat{y_a} & \hat{y_a} \cdot \hat{z_a} \\ \hat{z_a} \cdot \hat{x_a} & \hat{z_a} \cdot \hat{y_a} & \hat{z_a} \cdot \hat{z_a} \end{bmatrix} \\ &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \underline{\mathbf{I_3}} \end{aligned} \tag{4.14}$$

Remember that the reference frame's basis vectors are of length 1, and all perpendicular to each other. Also, $\underline{\mathbf{c_a}}$ has length 3, so

$$\begin{aligned} \vec{\mathcal{F}_a} \cdot \vec{c} &= \underline{\mathbf{I_3}}\, \underline{\mathbf{c_a}} && \text{returning to 4.13} \\ \vec{\mathcal{F}_a} \cdot \vec{c} &= \underline{\mathbf{c_a}} && (4.15) \end{aligned}$$

[3]Thanks to Peter C. Hughes for this notation.

Vector Operations in Reference Frames

Addition:

1.5 Common Reference Frames

Three-dimensional space can contain infinitely many reference frames. The plane chosen for reference affects many aspects of calculation, and translation between planes can turn a difficult calculation into a simple one. Therefore, it is important to know the differences between choice of plane and the advantages each confers.

Each frame may have a unique origin, displaced by some vector from another plane's origin. Each frame may also be rotated relative to another.

Each frame will have a **fundamental** plane that only considers the x and y coordinates. Many operations are two-dimensional and constrained the frame's fundamental plane.

For now, let us examine only a few reference frames.

Orbital Planes Orbits, as will be demonstrated in section 2.2, tend to occupy a single 2-D plane. For now, take this for granted. The orbital plane B_P embeds the trajectory of body B. Orbital planes originate from the body that B is orbiting. They can be oriented in any manner relative to their parent bodies.

To make planes useful, they will also include a coordinate system. The convention in this book and most of orbital dynamics is right-handed: imagine a right hand, index finger pointed forward, thumb pointed up, and middle finger pointed perpendicular to the palm. The thumb represents the $+x$ axis, the index the $+y$ axis, and the middle finger the $+z$ axis. This hand can be rotated and the orthogonal relationships between the axes remain.

Place the hand in the plane, aligning the thumb with the $+x$ axis, and the index also in the plane. Note that there will be two orientations that satisfy this requirement, $180°$ around the x-axis. For this reason, any coordinate system in a plane can be described by two values: the rotation from some other coordinate system and whether the index finger is clockwise or counter-clockwise from the thumb. Counter-clockwise index means a positive z-axis, and clockwise means a negative, or inverted z-axis.

The rotation from some other coordinate system called the **zero longitude point**.

The Heliocentric Ecliptic Plane called ε, refers to an arbitrary plane centered on the sun. In the Sol system, the ecliptic refers to the plane of the Earth's orbit around Sol. While Sol's ecliptic is defined through Earth for historical reasons, the ecliptic for any given star system tends to average out the orbital planes of the bodies in that system. Due to planetary formation from protoplanetary dust disks (and the conservation of angular momentum), most planets tend to occupy similar orbital planes.

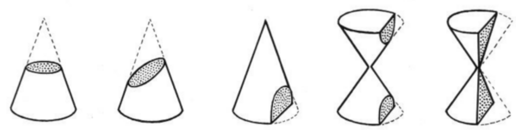


Figure 4.2: Slicing a double-napped cone with a plane at various heights and angles.

In Sol system, the ecliptic plane orients $+x$ along the vernal equinox – a vector from the sun to the earth on the first day of northern-hemisphere spring. This vector is often called ♈, because the vector appears to point to the constellation Aries. The length of ♈ is 1 **astronomical unit** (AU): the approximate distance from Sol to the Earth[4].

Earth processes slightly over thousands of years, meaning this plane changes over time. This book ignores that fact, instead assuming the J2000 Epoch measurements remain constant over time.

The Geocentric Equatorial Plane called ♁, refers to a plane originating at the center of Earth. The plane embeds the equator of Earth, with $+z$ along Earth's North Pole. Its zero longitude point is also ♈, the vernal equinox; it does not rotate with Earth but remains still relative to the celestial sphere.

Of course, this plane also changes with the procession of Earth, but this is ignored for the purposes of this book.

The Galactic Plane refers to the plane which embeds a line drawn from the center of Sol to the approximated center of the Milky way. It is oriented along the majority of the galactic mass. Rarely used in Exotic Matters, this plane locates the galactic background. This plane originates in Sol because the center of the Milky Way is not directly visible.

Further realizations about planes will become evident in this chapter.

1.6 Conics

A conic section is the intersection of a plane and a double-napped cone (fig. 4.2), where the plane This seemingly-unusual geometry has significant uses in spaceflight.

Both the edge and area of these shapes will be of some interest to us. No matter the inclination and height of the plane, the edge can be expressed in polar coordinates relative to the plane as:

$$r = \frac{pe}{1 + e\ cos\,\nu} \tag{4.16}$$

where e is a measure called **eccentricity** and p is the **focal parameter**.

[4]Approx. 150 million km.

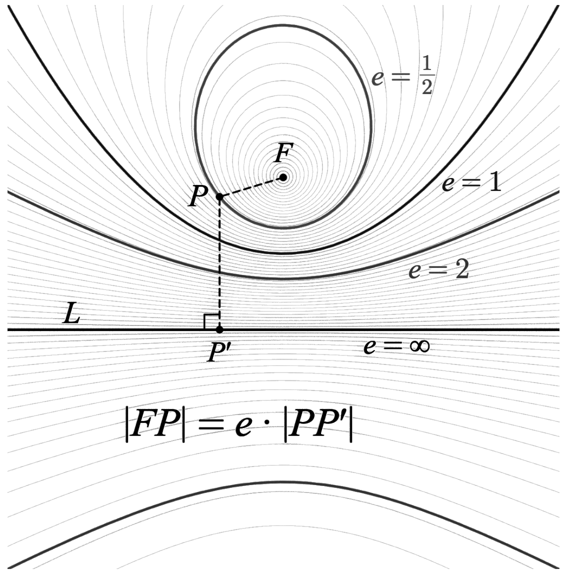


Figure 4.3: Conics with the same focus and directrix, but varying eccentricity.

Focus and Directrix

To understand the eccentricity e and focal parameter p, we must use the focus F and directrix L. F is some fixed point, and L some fixed line (4.3). p is the distance between F and L. The edge of the conic is defined as thex points P that are a distance d_F from the focus F and distance d_L from directrix L such that $d_F e = d_L$. In other words, a conic is the set of points where the ratio between its absolute distance to a point (a focus) and its absolute distance to a line (the directrix) is a positive constant e. Fig. 4.3 shows how varying eccentricity varies the shape of the conic.

Eccentricity

Eccentricity allows us to define conics without the use of cones. Consider fig. 4.4, and how the inclination of the plane changes the section.

Here we will depart the double-napped cone and only deal with conic sections in terms of planes. The shape of the intersection can be described by the single measure of **eccentricity** (e).

Eccentricity is the ratio between the semi-latus rectum l, which is the vertical distance between a focus and the curve of the conic, and the focal parameter p, which is the distance between primary focus F and the directrix L.

$$\frac{l}{p} = e \tag{4.17}$$

$$l = pe \tag{4.18}$$

An ellipse also has a second directrix L' that corresponds with F', completing its other half. A circle has no directrix and the relationship between these terms is

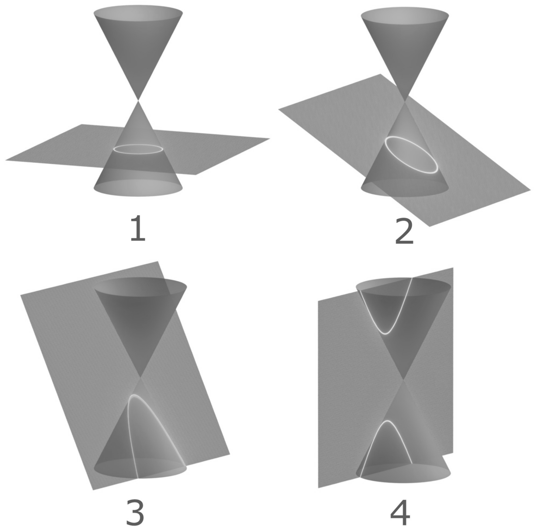


Figure 4.4: 1. Circle, 2. Ellipse, 3. Parabola, 4. Hyperbola

meaningless. Instead, with an eccentricity of 0, the semi-latus rectum is considered to be the radius ($l = r$).

The distance between the center to a focus is c. Eccentricity also describes the relationship between the semi-major axis and c:

$$c = ae \tag{4.19}$$

also the definition for the semi-latus rectum in terms of a and e is:

$$l = a(1 - e^2) \tag{4.20}$$

These apply to all conics except for the parabola. A parabola's long side is infinite ($a = \infty$) and therefore the distance from F to the center is also infinite.

Also,

A circle, not an eccentric fellow whatsoever, has an eccentricity of $e = 0$.

Axes

The minimum radius lies at $v = 0$, while the maximum radius lies at $v = \pi$.

At these extremes, $cosv$ evaluates to -1 and 1 respectively. Therefore,

$$r_{min} = \frac{p}{1+e} \tag{4.21}$$

$$r_{max} = \frac{p}{1-e} \tag{4.22}$$

While a circle has only one diameter that is equal in all orientations, other conics have additional measures as they change The **semi-major axis** (a) is the arithmetic mean between r_{min} and r_{max} and is the distance from the center (not focus) of the shape to its farthest point:

$$a = \frac{r_{max} + r_{min}}{2} = \frac{p}{1 - e^2} \tag{4.23}$$

The **semi-minor axis** (b) is the geometric mean between r_{min} and r_{max} and is the distance from the center (not focus) of the shape to its nearest point:

$$b = \sqrt{r_{max} r_{min}} = \frac{p}{\sqrt{1 - e^2}} \tag{4.24}$$

and

$$pa = r_{max} r_{min} = b^2 \tag{4.25}$$

$$p = \frac{r_{max} r_{min}}{a} = \frac{b^2}{a} \tag{4.26}$$

Circle

A circle is a special case of the ellipse where the two foci F and F' coincide. For a circle, $e = 0$, and $r = a$. The semi-minor axis is typically not defined, but can be considered to be equal to the semi-major axis ($a = b$). The semi-latus rectum and radius are identical ($l = r$).

Ellipse

Parabola

For a parabola, $a = \infty$ and $c = \infty$

Hyperbola

Degenerate Conics

Degenerate conics emerge when the plane intersects the cone through the apex. If the plane is horizontal, the result is a single point. If the plane is vertical, the result is This results in one or two straight lines, or a single point.

2 Foundations

Here you will learn how to fly a starship. It's not rocket science, but it's close.

Spaceflight is complex and Exotic Matters tries to stay "as faithful as reasonable" to real-world mechanics. That being said, there are a number of simplifications and assumptions made to vastly ease the burden of computing trajectories by hand:

1. Special and General Relativity are ignored. Space is considered uniform and flat, and time the same in all reference frames.
2. Only two bodies are considered at once: the satellite (hereafter S) and the planet or moon (hereafter B).
3. The satellite S is only accelerated by the strongest local gravitational force F_{g_B}, making all our trajectories unpowered (ballistic) flight, meaning that–
4. Maneuvers are considered instantaneous; while this is impossible, consider the powered flight as an impulse halfway through the burn time.
5. The satellite is treated as a point particle of mass m_S which is constant during ballistic flight.
6. The mass of the satellite is negligible compared to the mass of B. ($m_S \times 10^6 \leq m_B$), meaning that–
7. Gravitational acceleration exerted on B by S is ignored.
8. Body B is perfectly spherical and uniform in density, of radius r_B and mass m_B. $\vec{r}$ is measured from the center of mass of B.
9. There is a global inertial reference from against which all other reference frames can be measured.
10. Body B, around which S orbits, is accelerating negligibly enough to be considered an inertial reference frame.

2.1 Kepler's Laws

Between 1609 and 1619, Johannes Kepler used the observations provided by his colleague Tycho Brahe to formulate mathematical laws about planetary motion. Though Kepler did not have Isaac Newton's laws of gravitation, he was nevertheless able to establish a few laws of orbital motion through observation alone. While these did not explain the reasons for planetary motion, they described and predicted the motions of a smaller body orbiting a much larger one.

The three laws are:

1. Planets orbit the sun in the path of an ellipse, with the sun at one focus.

2. A line from the sun to the planet sweeps equal areas over equal durations of time.

3. The square of the planets orbital period (T) is proportional to the cube of the length of the semi-major axis of the orbit ($T^2 \propto a^3$).

All of these laws can be derived from Newton's laws of gravitation. The first law will be demonstrated in section 2.3. The second law will be demonstrated in section 3. The third law will be left as an exercise for the reader.

2.2 Foundational Equations

We must outline the foundational equations.[5] These general equations underlie the specific-case equations that have been reduced to input-output formats to allow quick problem-solving in-situ. Understanding the general principles is important for mastery, but less important when time is of the essence.

In this book, vectors are given in arrow notation (e.g. $\vec{r}$) and a vector shown without its arrow is the vector's magnitude (i.e. $|\vec{r}| = r$). The unit vector of a vector is given the hat ($\hat{r}$). Derivatives are given with overdots (e.g. $f' = \dot{f}$, $f'' = \ddot{f}$). For instance, velocity $\vec{v}$ may be represented as $\dot{\vec{r}}$ and acceleration $\vec{a}$ may be represented as $\ddot{\vec{r}}$.

Newton's Gravitation

Newton's law of gravitation can be written as

$$\vec{F}_g = -G\frac{m_B m_S}{r^2}\hat{r} \tag{4.27}$$

where the negative sign and $\hat{r}$ component direct the force vector toward B.

Essentially, this means that all objects in the universe with mass are attracted to each other. Each object experiences an apparent force towards each other object, proportionally strong to the product of their two masses, but falling off with the square of the distance between the two. The constant G was not discovered by Newton, but by Henry Cavendish in 1798. Notice how even if G is not known, the proportional strengths of forces can be determined.

Combining Newton's Law of Universal Gravitation with Newton's Second Law ($\Sigma\vec{F} = m\ddot{\vec{r}}$), the acceleration due to gravitation can be expressed (remembering that only one single force of gravity is being considered at the moment) as:

$$m_S\ddot{\vec{r}} = -G\frac{m_B m_S}{r^2}\hat{r}$$

$$\ddot{\vec{r}} = -G\frac{m_B}{r^2}\hat{r}$$

[5] If you are about to collide with a planet, skip this section and move on to Suicide Burn. You will have time to learn the fundamentals later.

Because G is very small, and m_B is very large, this book will combine the two terms into a single constant μ which will be provided for each body the spacecraft might orbit. This also simplifies the gravitational acceleration to:

$$\ddot{\vec{r}} = -G\frac{m_B}{r^2}\frac{\vec{r}}{r}$$

$$\ddot{\vec{r}} = -G\frac{m_B}{r^3}\vec{r}$$

$$\boxed{\ddot{\vec{r}} = -\frac{\mu}{r^3}\vec{r}} \tag{4.28}$$

Here, $\ddot{\vec{r}}$ is the instantaneous acceleration when the satellite S is at location $\vec{r}$ (remember, relative to the center of body B). Instantaneous velocity ($\dot{\vec{r}}$) clearly has no effect on $\ddot{\vec{r}}$; the acceleration gained will be identical when the spacecraft passes through the point described by $\vec{r}$ regardless of its speed or direction – though the resulting velocity vector may obviously be different.

To understand a little more of the resulting motion, let us demonstrate the conservation of angular momentum in this system. To get the specific angular momentum[6], we must find the cross product of displacement $\vec{r}$ and linear velocity $\vec{v}$. Starting from Equation 4.28, we arbitrarily cross multiply by $\vec{r}$:

$$\begin{aligned}
\ddot{\vec{r}} &= -\frac{\mu}{r^3}\vec{r} \\
\ddot{\vec{r}} + \frac{\mu}{r^3}\vec{r} &= 0 \\
\vec{r}\times\ddot{\vec{r}} + \vec{r}\times\frac{\mu}{r^3}\vec{r} &= 0 \qquad\qquad a\vec{r}\times\vec{r} = 0 \\
\vec{r}\times\ddot{\vec{r}} &= 0
\end{aligned} \tag{4.29}$$

Now, let us introduce the fact that

$$\begin{aligned}
\frac{d}{dt}(\vec{a}\times\vec{b}) &= \frac{d\vec{a}}{dt}\times\vec{b} + \vec{a}\times\frac{d\vec{b}}{dt} \\
\frac{d}{dt}(\vec{r}\times\dot{\vec{r}}) &= \dot{\vec{r}}\times\dot{\vec{r}} + \vec{r}\times\ddot{\vec{r}} \\
\frac{d}{dt}(\vec{r}\times\dot{\vec{r}}) &= \vec{r}\times\ddot{\vec{r}}
\end{aligned} \tag{4.30}$$

using equations 4.29 and 4.30, we now get:

$$\frac{d}{dt}(\vec{r}\times\dot{\vec{r}}) = 0 \tag{4.31}$$

[6]Momentum *per unit of mass*. That is, angular momentum divided by mass ($\frac{\vec{L}}{m}$).

which shows no change (a zero derivative) in the specific angular momentum over the course of the whole orbit along the whole equation. Therefore, specific angular momentum is conserved, and, since $\dot{\vec{r}} = \vec{v}$, we can express specific angular momentum $\vec{h}$ as:

$$\boxed{\vec{h} = \vec{r} \times \vec{v}} \tag{4.32}$$

and conclude that because $\vec{h}$ is constant (always in the same direction), and always perpendicular to the plane of $\vec{r}$ and $\vec{v}$, that both of those vectors always lie in a single plane (called the *orbital plane*) and the motion of S is always in the orbital plane, though that plane may be oriented many ways compared to the local or "global" frame of reference.

Consider the other consequence of this fact: r and v are inversely proportional. This means that if the satellite decreases in altitude, its speed must increase. Likewise, if the satellite increases in altitude, its speed must decrease. We can therefore conclude that the fastest speed will be at the lowest altitude in the orbit, and the slowest speed will be at its highest altitude (Compare this with what you know intuitively about how objects accelerate as they are thrown). Let us call the highest point the apoapsis, and the lowest point the periapsis[7].

2.3 General Trajectory Equation

However, to understand the motion of the spacecraft over time, we must naturally integrate this acceleration over time to find the change in velocity over time, and integrate again to find the location at any given time. Returning to equation **??**, we transform it into a form that can be integrated:

$$\begin{aligned}
\ddot{\vec{r}} &= -\frac{\mu}{r^3}\vec{r} \\
\ddot{\vec{r}} \times \vec{h} &= -\frac{\mu}{r^3}(\vec{r} \times \vec{h}) && (4.33) \\
&= \frac{\mu}{r^3}(\vec{h} \times \vec{r}) && \text{Anticommutative} \\
&= \frac{\mu}{r^3}((\vec{r} \times \vec{v}) \times \vec{r}) && \text{by 4.32} \\
&= \frac{\mu}{r^3}\vec{v}(\vec{r} \cdot \vec{r}) - \vec{r}(\vec{r} \cdot \vec{v}) = \frac{\mu}{r^3}\vec{v}(\vec{r} \cdot \vec{r}) - \frac{\mu}{r^3}\vec{r}(\vec{r} \cdot \vec{v}) \\
& && \text{note } \vec{r} \cdot \vec{r} = r^2 \text{ and } \vec{r} \cdot \dot{\vec{r}} = r\dot{r}\text{:} \\
\ddot{\vec{r}} \times \vec{h} &= \frac{\mu}{r}\vec{v} - \frac{\mu\dot{r}}{r^2}\vec{r} && (4.34)
\end{aligned}$$

To continue, let us exploit an interesting coincidence:

[7] an apsis, also *apse*, (pl. *apsides*) is a point in an orbit; *ap-* and *peri-* meaning far and near, respectively. Also written as *apogee/perigee*, *aphelion/perihelion* contextually.

$$\frac{d}{dt}\hat{r} = \frac{d}{dt}\left(\frac{\vec{r}}{r}\right) = \frac{\vec{v}}{r} - \frac{\dot{r}\vec{r}}{r^2}$$

$$\mu\frac{d}{dt}\left(\frac{\vec{r}}{r}\right) = \frac{\mu}{r}\vec{v} - \frac{\mu\dot{r}}{r^2}\vec{r} \tag{4.35}$$

and so by 4.34 and 4.35,

$$\frac{d}{dt}(\dot{\vec{r}} \times \vec{h}) = \mu\frac{d}{dt}\left(\frac{\vec{r}}{r}\right) \tag{4.36}$$

whose indefinite integral (with yet-unknown constant of integration $\vec{C}$) is

$$\dot{\vec{r}} \times \vec{h} = \mu\frac{\vec{r}}{r} + \vec{C} \tag{4.37}$$

$$\begin{aligned}
\vec{r}\cdot\dot{\vec{r}} \times \vec{h} &= \vec{r}\cdot\mu\frac{\vec{r}}{r} + \vec{r}\cdot\vec{C} && \text{Dot by } \vec{r} \\
&= \mu\frac{\vec{r}\cdot\vec{r}}{r} + \vec{r}\cdot\vec{C} \\
&= \mu\frac{r^2}{r} + \vec{r}\cdot\vec{C} && \vec{a}\cdot\vec{a} = a^2 \\
&= \boxed{\mu r + \vec{r}\cdot\vec{C}} && (4.38) \\
\vec{r}\cdot\dot{\vec{r}} \times \vec{h} &= \vec{r}\times\dot{\vec{r}}\cdot\vec{h} = \vec{h}\cdot\vec{h} && \text{by 4.32} \\
&= h^2 && (4.39) \\
\mu r + \vec{r}\cdot\vec{C} &= h^2 && \text{by 4.38 and 4.39.}
\end{aligned}$$

For convenience, the trajectory could be expressed in polar coordinates. Working in polar coordinates means that we must define the angle to give the function. Because of the definition of the dot product, $\vec{a}\cdot\vec{b} = ab\ cos\,\nu$, the angle between $\vec{C}$ and $\vec{r}$ is fit for this purpose. This orients $\nu = 0$ along $\vec{C}$. Now we must simply solve for the magnitude of $\vec{r}$ to determine the displacement of the satellite at angle ν:

$$\begin{aligned}
\mu r + rC\ cos\,\nu &= h^2 && \text{Dot product definition} \\
r(\mu + C\ cos\,\nu) &= h^2 \\
r &= \frac{h^2}{\mu + C\ cos\,\nu} \\
&\boxed{r = \frac{h^2/\mu}{1 + C/\mu\ cos\,\nu}} && (4.40)
\end{aligned}$$

Hopefully, this equation looks familiar, unless you skipped the previous chapter. Both 4.16 and 4.40 describe the radius of a conic as a function of ν.

$$r = \frac{h^2/\mu}{1 + C/\mu\, cos\, \nu} = r = \frac{pe}{1 + e\, cos\, \nu} \tag{4.41}$$

It is then easy to solve for the equivalences $h^2/\mu = l = pe$ (semi-latus rectum) and $C/\mu = e$, knowing that C, h, and μ are constant. We now have our familiar conic:

$$r = \frac{pe}{1 + e\, cos\, \nu} \tag{4.16}$$

Recall that this conic is in a specific orientation and it might be transformed later, but for now this can be ignored. See that $\vec{C}$ points toward periapsis: when $\vec{C}$ and $\vec{r}$ are coincident, $cos\, \nu = 1$, making r the smallest it will ever be: this is the location of the periapsis. Now, our convention is that periapsis is at angle $\nu = 0$, and apoapsis (which may even be infinity) is at angle $\nu = \pi$ (try it!). It is now possible to determine the altitude of the satellite at a specific angle. Now, ν will be called the **true anomaly**[8].

We also have two new facts:

$$C = \frac{e}{\mu} \tag{4.42}$$

and

$$h^2/\mu = l = pe \tag{4.43}$$

An important conclusion from 4.41 is that the trajectory of a satellite in our simplified "one-body" problem will always be a conic. Additionally, since r is the measure from the primary focus to the edge of the conic, we can conclude the body B will lie at the primary focus. Kepler's first law, "the orbit of every planet is an ellipse with the Sun at one of the two foci", has also been recovered from 4.41: the trajectory will be an ellipse with its primary focus at the Sun in the case of $0 \leq e < 1$.

The more poetic reader may take a moment to appreciate the beauty in physics, as later scientific discoveries produce identical conclusions to previous consensus in the special case. The more adventurous reader has already skipped this chapter.

2.4 Apsides (Periapsis and Apoapsis)

As established, the periapsis will be at $\nu = 0$ and apoapsis will be at $\nu = \pi$. Plugging these into 4.16, we get:

[8] This is the first of six **Orbital Parameters**. Each one will be bolded when introduced in this chapter.

$$
\begin{aligned}
r_{peri} &= \frac{pe}{1+e} && \text{see section 1.6} \\
r_{peri} &= \frac{l}{1+e} && \text{by 4.17, then 4.20...} \\
r_{peri} &= \frac{a(1-e^2)}{1+e} \\
r_{peri} &= \frac{a(1-e)(1+e)}{1+e} \\
r_{peri} &= a(1-e) && (4.44)
\end{aligned}
$$

and, similarly for apoapsis:

$$
\begin{aligned}
r_{apo} &= \frac{l}{1-e} \\
r_{apo} &= a(1+e) && (4.45)
\end{aligned}
$$

2.5 Eccentricity Vector

The eccentricity vector is a vector with the length e that points from B to the periapsis. Recall the bizarre substitution done in 4.42. If we say that $C = \mu e$, then $\vec{C} = \mu\vec{e}$.

$$
\begin{aligned}
\dot{\vec{r}} \times \vec{h} &= \mu\frac{\vec{r}}{r} + \vec{C} && \text{recalling 4.37} \\
\dot{\vec{r}} \times \vec{h} - \mu\frac{\vec{r}}{r} &= \vec{C} \\
\dot{\vec{r}} \times \vec{h} - \mu\hat{r} &= \vec{C} \\
\frac{1}{\mu}(\dot{\vec{r}} \times \vec{h}) - \hat{r} &= \frac{\vec{C}}{\mu} \\
\frac{1}{\mu}(\dot{\vec{r}} \times \vec{h}) - \hat{r} &= \vec{e} && (4.46)
\end{aligned}
$$

This is our definition of the eccentricity vector. It is constant and conserves momentum and scales the size of this orbit by the gravity of B.

2.6 Conservation of Energy

Another fundamental rule of physics is the conservation of energy. If we can derive a constant energy from our acceleration equation 4.28, we can help legitimize our findings.

$$\ddot{\vec{r}} = -\frac{\mu}{r^3}\vec{r} \tag{4.28}$$

$$\ddot{\vec{r}} + \frac{\mu}{r^3}\vec{r} = 0$$

$$\dot{\vec{r}} \cdot \ddot{\vec{r}} + \dot{\vec{r}} \cdot \frac{\mu}{r^3}\vec{r} = 0$$

$$\dot{\vec{r}} \cdot \ddot{\vec{r}} + \frac{\mu}{r^3}\vec{r} \cdot \dot{\vec{r}} = 0$$

$$\dot{r}\ddot{r} + \frac{\mu}{r^3}r\dot{r} = 0 \qquad \text{since } \vec{a} \cdot \vec{b} = a \cdot b$$

$$\dot{r}\ddot{r} + \frac{\mu}{r^2}\dot{r} = 0$$

$$\frac{d}{dt}\left(\frac{\dot{r}^2}{2}\right) + \frac{\mu}{r^2}\dot{r} = 0 \qquad \text{since } \tfrac{d}{dt}\left(\tfrac{\dot{r}^2}{2}\right) = \dot{r}\ddot{r}$$

$$\frac{d}{dt}\left(\frac{\dot{r}^2}{2}\right) + \frac{d}{dt}\left(-\frac{\mu}{r}\right) = 0 \qquad \text{since } \tfrac{d}{dt}\left(-\tfrac{\mu}{r}\right) = \tfrac{\mu}{r^2}\dot{r}$$

$$\frac{d}{dt}\left(\frac{\dot{r}^2}{2} - \frac{\mu}{r}\right) = 0$$

$$\frac{d}{dt}\left(\frac{\dot{r}^2}{2} - \frac{\mu}{r} + c\right) = 0 \qquad \text{since for constant } c,\ \tfrac{d}{dt}c = 0$$

If that whole term has a derivative of zero, it must be a constant. We will call this E, for energy: $E = \frac{\dot{r}^2}{2} - \frac{\mu}{r} + c$.

The equation for kinetic energy is $E = \frac{1}{2}mv^2$, or in our terms $E = \frac{1}{2}m\dot{r}^2$. Diving both sides by m gives the **specific kinetic energy** $E_{sp} = \frac{1}{2}\dot{r}^2$. Remember, *specific* means *per unit of mass*.

Next, $\frac{\mu}{r}$ refers to the potential energy per unit of mass. This is because the equation for work under Newton's law of gravitation is the integral of the force equation:

$$\vec{F_g} = \frac{\mu m_S}{r^2}\hat{r} \tag{4.27}$$

$$W_g = \int_{\vec{r_2}}^{\vec{r_1}} \left(\frac{\mu m_S}{r^2}\right) \cdot d\vec{r}$$

$$W_g = \mu m_S \int_{\vec{r_2}}^{\vec{r_1}} r^{-2} \cdot d\vec{r}$$

$$W_g = \mu m_S \left[-\frac{1}{r}\right]_{r_1}^{r_2}$$

$$W_g = \mu m_S \left(-\frac{1}{r_2} + \frac{1}{r_1}\right)$$

$$W_g = \mu m_S \left(-\frac{1}{r_2} + \frac{1}{\infty}\right) \qquad \text{Choosing } \infty \text{ as 0 potential energy}$$

$$W_g = \mu m_S \left(-\frac{1}{r_2}\right) \qquad \infty \text{ tends to 0}$$

The definition of potential energy is work from baseline to another energy state:

$$U = -\frac{\mu m_S}{r} \tag{P}$$

Dividing mass out, we are left with specific potential energy:

$$U_{sp} = -\frac{\mu}{r} \tag{4.47}$$

Finally, c is a constant representing the base level of potential energy. If ground level is considered zero potential energy, then a value of $\frac{\mu}{r}$ makes sense, since it cancels out the similar term. For convenience, however, we choose 0. This means that the zero-potential-energy altitude is at infinity. In a completely empty universe except B and S, S as infinite potential energy at infinite distance. Any closer and it has negative potential energy.

This means that specific mechanical (kinetic + potential) energy is:

$$E_{sp} = \frac{\dot{r}^2}{2} - \frac{\mu}{r} \tag{4.48}$$

$$= \frac{v^2}{2} - \frac{\mu}{r} \tag{4.49}$$

2.7 Summary

$$r = \frac{h^2/\mu}{1 + C/\mu \; cos\, \nu} \qquad \text{r as a function of mean anomaly 4.40}$$

$$\vec{h} = \vec{r} \times \vec{v} \qquad \text{Specific Angular Momentum 4.32}$$

3 Coplanar Flight

By considering only the plane in which the orbit is embedded, several variables can be ignored for the time being.

These equations are the foundation of flight in a fully three-dimensional space. Extension of these operations into other orbital planes outside the local reference plane, as well as transformations between the two, can be found on page 99 in *Three-Dimensional Flight*.

The last chapter demonstrated how a spacecraft's trajectory is a conic section. This chapter will show how to embed that conic into a plane, rotate it about the body, and contextualize the trajectory above the body.

3.1 Longitude of Periapsis

Consider the body B and orbiting satellite S. Ignore all motion of B around its sun, the center of the galaxy, etc. Now consider a vector embedded in the plane pointing in a fixed, but arbitrary[9] direction. Call this the **pericenter**.

The orbit, if not circular, will have its periapsis at some angle ϖ[10]. This angle ϖ is called the **longitude of periapsis**. Longitude, in astrodynamics, refers to an angle from the pericenter within the plane.

Consider several identical orbits that only vary by ϖ. Their semi-major axes will be identical, their periods will have the same duration, and their eccentricities will likewise be identical. As ϖ varies, the orbits will rotate around the body.

Recall that B lies at the primary focus of each orbit. Consider cases of two orbits, three orbits, etc. and how evenly spacing their longitudes of periapsis around the circle will result in rosettes of several petals.

Before locating the spacecraft, only one more parameter is required.

3.2 True Anomaly at Epoch

The phrase **true anomaly at epoch**, denoted by ν_0, describes the position of S at a specific time.

True anomaly describes the angle between pericenter ($0°$) and its current position around the ellipse (counter-clockwise). It is called the "true" anomaly for reasons that will become clear only once additional anomalies are introduced. Anomalies are values that track and relate to S's position through its orbit.

True anomaly varies with time. Many satellites can share the same orbit with different true anomalies. Two satellites with the same true anomaly would be inside each other.

Consider a train of satellites all along the same orbit, rising and falling in a vast train, like beads on a necklace. They would all share all orbital parameters except their current true anomalies.

[9] for now

[10] "Variant π" or "Cursive π"

Because true anomaly constantly changes, we must choose an arbitrary time point (an **epoch**, denoted by τ) at which to record true anomaly. Thus, orbital parameters include the unchanging value true anomaly **at epoch**. True anomaly at epoch, therefore, describes the angle through its orbit (as measured from pericenter counter-clockwise) the satellite was at the instant of epoch.

In some texts, this is not clearly explained and simply called *true anomaly*. If no context is given on a singular true anomaly angle, it must be assumed that true anomaly was measured at one particular epoch.

3.3 Paramaters for Coplanar Flight

Now, we have collected all the necessary parameters to describe the position of a satellite S and its orbit in one reference plane at time t.

- a is the semi-major axis.
- e is the eccentricity.
- ϖ is the longitude of periapsis.
- ν_τ is the true anomaly at epoch (time τ).

When multiple bodies are present, their respective parameters will be given as subscripts of their names (e.g. for satellite S: $S_a, S_e, S_\varpi, S_{\nu_\tau}$).

Though semi-minor axis (b) is not a primary parameter, it can be obtained using:

$$b = a\sqrt{1-e^2} \tag{4.50}$$

3.4 Mean Angular Motion

Define the orbital period of S as T, a duration of time. Call its reciprocal n, or $n = \frac{2\pi}{T}$; in other words, n is the average angular rate S travels.

Kepler's third law states that $T^2 \propto a^3$ – that is, the square of the period is proportional to the cube of the semi-major axis. That proportion can be represented as $\frac{T^2}{a^3}$. We can then set the proportion equal to some ratio of constants where the numerator is unknown:

$$\frac{a^3}{T^2} = \frac{\mu}{4\pi^2} \tag{4.51}$$
$$\frac{a^3}{\left(\frac{2\pi}{n}\right)^2} =$$
$$\frac{a^3 n^2}{4\pi^2} =$$
$$a^3 n^2 = \mu \tag{4.52}$$
$$n = \sqrt{\frac{\mu}{a^3}} \tag{4.53}$$

Mean angular motion can be defined in terms of gravitational parameter and semi-major axis. Another way to conceptualize mean angular motion is the rate S would have, were to travel a circular orbit of diameter a[11].

But what is the proof that μ is the same value for μ we have been using the whole time? Once again, we return to Newton's law of gravitation (4.27), which can be combined with angular acceleration ($a = r\omega^2$):

$$mr\omega^2 = G\frac{Mm}{r^2}$$
$$r\omega^2 = \mu\frac{1}{r^2} \qquad GM = \mu$$
$$r^3\omega^2 = \mu$$
$$r^3\left(\frac{2\pi}{T}\right)^2 = \mu$$
$$\frac{r^3 4\pi^2}{T^2} = \mu$$
$$\frac{r^3}{T^2} = \frac{\mu}{4\pi^2} \tag{4.54}$$

Since mean angular motion considers a circle circumscribed around the orbit (with $r = a$), we can conclude that our use of μ was legitimate.

3.5 Mean Anomaly

True anomaly is not appropriate for all contexts. Therefore, another value called **mean anomaly** will also be used. Like true anomaly, mean anomaly is an angle measured from the perifocus.

As S sweeps out its course through its orbit, its speed and angular velocity may change. As noted above, the mean angular motion is simply the average of angular motion. Mean anomaly is the anomaly (angle from pericenter) S would have, were it to have a constant angular motion:

[11]For a circle, semi-major axis and diameter are identical.

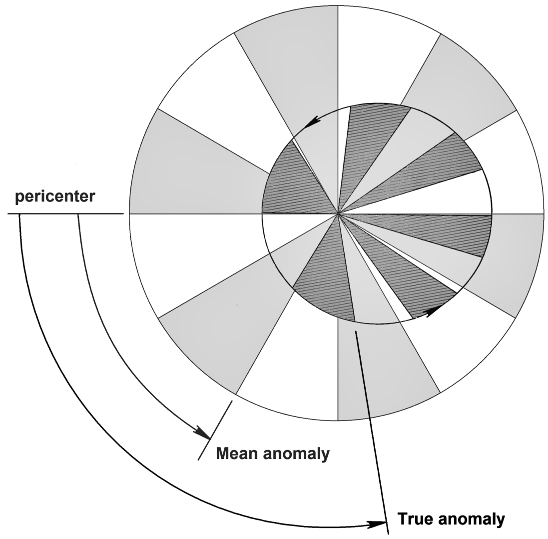


Figure 4.5: The areas swept out with constant angular motion vs. true angular motion. Major axes not to scale.

$$M = M_\tau + n(t - \tau) \qquad \text{then by 4.53...}$$

$$M = M_\tau + \sqrt{\frac{\mu}{a^3}}(t - \tau) \tag{4.55}$$

Thus, we define **mean anomaly** as the angle through the orbit from pericenter S *would be* at if it swept through its orbit at constant angular velocity. Or alternatively, the true anomaly of S at time t if its orbit were a circle of diameter a[12]. See Figure 4.5 which illustrates the difference in angle for an elliptical orbit and circular orbit.

Another definition of mean anomaly is given by Kepler:

$$M = \vec{E} - e\, sin\, \vec{E} \tag{4.56}$$

Now, considering only one orbit, we set our epoch as the time S passes periapsis ($M_\tau = 0$):

$$M = \sqrt{\frac{\mu}{a^3}}(t - \tau) \qquad \text{by 4.55}$$

$$M = \sqrt{\frac{\mu}{a^3}}(t - \tau) = \vec{E} - e\, sin\, \vec{E} \tag{4.57}$$

[12]Known as the **Auxiliary circle**.

3.6 Eccentric Anomaly

Eccentric Anomaly relates mean anomaly and true anomaly. It varies over time. The Eccentric anomaly is like the true anomaly in that it measures the angle between the periapsis and the orbiting body, but from the center of the ellipse.

$$\tan E = \frac{\sin E}{\cos E} = \frac{\sqrt{1-e^2}\ \sin f}{e + \cos f} \tag{4.58}$$

TODO

3.7 Time of Flight

TODO

3.8 Anomaly at Time

TODO

$$\nu = E + 2\,arctan\left(\frac{\beta\ \sin\ E}{1 - \beta\ cos\,E}\right) \tag{4.59}$$

where

$$\beta = \frac{e}{1 + \sqrt{1-e^2}} \tag{4.60}$$

3.9 Radius from True Anomaly

$$r = a\frac{1-e^2}{1 + e\,cos\ \nu} \tag{4.61}$$

3.10 Cartesian Coordinates

$$x = a\ (cos\,\vec{E} - e) \tag{4.62}$$

$$y = b\ sin\,\vec{E} \tag{4.63}$$

Note that these coordinates are *perifocal*.

4 Three-Dimensional Flight

dead.jpg

4.1 Longitude of Periapsis

$\varpi = \Omega + \omega$

In other words, longitude of periapsis is the sum of longitude of ascending node and argument of periapsis.

4.2 Coordinate Transformation

4.3 Changing Planes

5 Patched Conics

Though conics provide a "good enough" approximation for flight while orbiting one body, presumably you are interested in space travel because you would like to visit other bodies. To keep calculations in this simple "one-body" problem while traveling between multiple systems, a star system can be divided into small domains, called "spheres of influence", which are spherical volumes possessed by bodies, where that body's gravitational influence is the strongest. At the boundaries of these spheres, the velocity and position vectors can be reframed according to the reference frame of the body whose sphere the craft has just passed into.

In this way, the simple conics approximation can be "patched" at the point where the new body's gravitational influence becomes stronger than the previous sphere's body. A complete trajectory can be constructed from the divided conic sections as the craft passes through multiple spheres of influence.

Spheres of Influence A sphere of influence is a volume in which some body's gravitational force on the spacecraft is larger than others. Consider the Earth-Moon system:

6 Maneuvers

6.1 Trip Planning

Planning a trip from one location to another is done top-down: choose a destination, list the transfers needed to go from place to place, list the maneuvers for each transfer, then calculate each maneuver.

TODO: Explain trip planning in more detail.

6.2 List of Equation Terms

This small glossary of equation terms represents the definition of terms across all the following calculations.

Ship terms:

- F, Thrust of engine in n
- M_I, "Initial" Mass of rocket before burn, including fuel, in kg
- M_F, "Final" Mass of rocket after burn, including fuel, in kg
- M_W, "Wet" Mass of rocket full of fuel, including fuel, in kg
- M_D, "Dry" Mass of rocket, not including fuel, in kg
- ΔM, fuel required for burn, in kg
- ΔT, elapsed time of burn in s
- $\vec{V}$, Velocity
- V, Speed (Magnitude of Velocity)
- V_E, Exhaust velocity of engine in ${}^{m}/_{s}$
- ΔV, change in velocity in ${}^{m}/_{s}$

Body terms:

- M_B, Mass of the body which you're orbiting in kg
- R_B, Radius of the body in m
- T_B, Length of sidereal day in s

Orbital Parameters:

- a, Semi-major axis. Furthest distance from body's center during orbit in m
- e, Eccentricity. Measures how circular an orbit is. Dimensionless, $e = 0$ for circular orbit, $0 <= e < 1$ for planetary orbit, $e > 1$ when travelling at or faster than escape velocity.
- i, Inclination. The angle between the reference plane and orbital plane.
- Ω, Longitude of the Ascending Node.
- ω, Argument of Periapsis.
- ν_τ, True Anomaly at Epoch. *or, alternatively:*
- ϖ_t, Time since periapsis passage

Other Orbital Properties:

- T, Period; the time period of one sidereal orbital revolution.

6.3 Simple Velocity Change

$$SVC(\Delta V, F, E_V, M_I) \Rightarrow (\Delta T, \Delta M)$$

This simple maneuver equation is the foundation of navigation — all other maneuvers are derived from this.

Required known quantities:

- ΔV, desired change in velocity in $^m/_s$
- F, Thrust of engine in n
- V_E, Exhaust velocity of engine in $^m/_s$
- M_I, Mass of rocket before burn, including fuel in kg

Derived quantities:

- ΔT, elapsed time of burn in s
- ΔM, fuel required for burn in kg

$$\Delta T = \left(\frac{M_I \times V_E}{F}\right) \times \left(1 - e^{-\frac{\Delta V}{V_E}}\right)$$

$$\Delta M = M_I - \left({}^{M_I}/_{e^{\frac{\Delta V}{V_E}}}\right)$$

6.4 Torch Burn

Also known as a *constant boost brachistochrone trajectory* or *burn-flip-burn*. As the term *brachistochrone* implies, this maneuver minimizes flight time. However, it also maximizes fuel cost.

Zeroing Velocity

6.5 Suicide Burn

Important! If your craft is fitted with an **SPFC-II** or later or compatible, immediately enter the following code to your mDSKY:

```
FEED NOUN 27  ; Cont. copy "true" altitude into ACC
VERB 11       ; Zero rel ground v at alt=ACC late as possible
EXEC
```

If you have no SPFC, or an incompatible model, retrieve a slide rule and proceed to do the calculation by hand – quickly.

6.6 Surface to Orbit

$$STO(...) \Rightarrow \Delta V$$

This equation gives the required delta-v to ascend to a circular orbit of a desired altitude from rest on the surface of a body.

Required known quantities:

- ...

Derived quantities:

- ΔV, required change in velocity in ${}^{m}/_{s}$

TODO: Finish equations and nomograms for Surface to Orbit

6.7 Orbit to Surface

TODO: Create equations and nomograms for Orbit to Surface

6.8 Surface to Surface (Ballistic)

TODO: Create equations and nomograms for Surface to Surface

6.9 Orbit to Orbit

Bi-impulse transfer (Hohmann Transfer)

Less Efficient Transfer

TODO: Create equations and nomograms for Orbit to Orbit

6.10 Orbital Rendezvous

An orbital rendezvous is a specific case of the Bi-impulse transfer where the timing of the transfer results in a very close approach to the target — matching both its position and velocity.

TODO: Create equations and nomograms for Orbital Rendezvous

6.11 Planetary Orbit to Planetary Orbit

TODO: Create equations and nomograms for Planetary Orbit to Planetary Orbit

6.12 Transfer to Moon

TODO: Create equations and nomograms for Transfer to Moon

6.13 Return from Moon

TODO: Create equations and nomograms for Return from Moon

7 Interstellar Travel

Though no known faster-than-light travel method has been discovered (and indeed it seems unlikely that one ever will be), humans have long desired to travel between the stars. The increasing efficiency of reaction drives puts this prospect on the horizon, yet still impractical. Still, the distances, times, and energies involved in any such journies remain extreme. This section is kept short as it is unlikely to be applied, yet it is included in the hopeful attempt to dissuade the reader from attempting such a trip.

Proxima Centauri, Sol's closest neighbor, lies 4.39 light-years distant. In more familiar terms, this is 278,000 AU or 4.16×10^{13} km. As you can see, this is beyond the range of even the most aggressive Brachistochrone maneuver included on your charts.

Additionally, there is another complication: spacetime. While flight below .1C is well-approximated by Newton's equations, the reality is that the universe is more complex. C represents not just the speed of light, but the speed of any massless particle as well as the speed of causality. $C = 299,792,458 m/s$, but this number is so absurdly large for many purposes $C \approx 3.0 \times 10^8$ give close results. Assuming you wish to arrive within a human lifetime, your trip will involve velocities above $\frac{1}{10}$ light speed – **relativistic** velocities. For this you will need the tools given to us by the likes of Minkowski, Lorentz, and Einstein.

B	γ	α
0	1	1
0.050	1.001	0.999
0.100	1.005	0.995
0.150	1.011	0.989
0.200	1.021	0.980
0.250	1.033	0.968
0.300	1.048	0.954
0.400	1.091	0.917
0.500	1.155	0.866
0.600	1.25	0.8
0.700	1.400	0.714
0.750	1.512	0.661
0.800	1.667	0.6
0.866	2	0.5
0.900	2.294	0.436
0.990	7.089	0.141
0.999	22.366	0.045
0.99995	100.00	0.010

Table 4.1: Fraction of C with Lorentz factor.

7.1 Lorentz Factor

The Lorentz factor, γ, is central to most relativistic equations used in spaceflight. It relates an object's relative speed to other quantities observed mass, time, and length.

The Lorentz factor produces modified values. Some Length L, Speed v, or time t will be modified into a transformed L_0, v_0, or t_0; the subscript 0 denotes a relative value, while a lack of subscript denotes a value as observed from a frame at rest relative to the object.

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{4.64}$$

Note that at these very high velocities, speed is measured simply as a fraction of C for ease of calculation. This fraction may be notated called B: $B = \frac{v}{C}$.

If no velocity units are given in the relativistic equation, it is safe to assume the unit is C. Consider then that $v = 0$ results in a $\gamma = 1$, while $\lim_{v \to C}$ results in $\gamma = \infty$.

Note also the choice to ignore relativity at only small fractions of C: $v = \frac{1}{20}$ means that $\gamma = 1.001$; a mere one-thousandth extra factor. At $v = \frac{1}{10}$, $\gamma = 1.005$.

The reciprocal of gamma is sometimes defined as α: $\alpha = \frac{1}{\gamma}$.

Table 4.1 is given as a quick-reference for various Lorentz factors.

Length Contraction

Space contraction is only to your advantage; the distance you must travel gets shorter the faster you go.

Length contraction occurs along the line of travel. The spacecraft will observe the distance from its start and end point contract. Likewise, observers at the start and endpoint will see the spacecraft contract a length by the same factor.

Length contraction is given as:

$$L = \frac{1}{\gamma(v)} L_0 \tag{4.65}$$

or, solved for L_0 with the Lorentz factor substituted in:

$$L_0 = \frac{L}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{4.66}$$

Let the reader note that L_0 is an instantaneous value, and will change during acceleration. Any pilot wishing to accelerate through relativistic velocities will need to account for the changing distance throughout the acceleration. This is left as an exercise for the reader.

7.2 Time Contraction

This "time travel" only goes one way. There is no way to undo the time dilation.

7.3 K.I.S.S.

Keep it simple, stupid. The more variables added to a journey, the more difficult it will be to accurately execute. Try to keep all your motion along one straight line, with only one period of acceleration and another of deceleration at the target.

Surprisingly, the gravitational pull on a spacecraft from the Milky Way at large is nearly negligible at human timescales. The force will be in the millinewton range, estimating the Milky Way as a point particle some 26,000 light-years distant. Of course, it is really distributed all around Sol with a bias to one side, so the actual force will be slightly weaker still. At a significant fraction of C, the total perturbation over the course of a few light-years can easily be corrected stepwise by the overwhelmingly large engine that accelerated the ship to such speeds.

Therefore, an interstellar trajectory can be reckoned as a straight line. Choose some weak force to terminate Sol's sphere of influence and start your destination's. Patch to a velocity vector, cast the ray across to your destination's sphere of influence, and patch into that system's gravity. Make sure to measure the influence of any body that happens to pass close enough to the craft to exert some pull.

Good luck.

8 Physics Symbols

Latin Capital

B The body around which S is orbiting, the "center of attraction"

C Speed of light, else constant of integration

$\vec{E}$ Eccentric anomaly

F Force, else Prime focus of conic

$\mathcal{F}_x$ Reference frame centered on x

L Directrix of conic

M Mean anomaly

M_τ Mean anomaly at Epoch

P_x Plane embedding x

S The satellite, rocket, etc. under consideration

T Orbital period

Latin Miniscule

a Semi-major axis, else acceleration

b Semi-minor axis

e Eccentricity

h Specific angular momentum

l Semi-latus rectum

m Mass

n Mean angular motion

p focal parameter

r Radius from B's center to S

t Time (current instant)

v Velocity

Greek Capital

Θ Elevation

Greek Miniscule

ε Heliocentric Ecliptic

μ Gravitational argument

ν True anomaly

ν_τ True anomaly at Epoch

π Pi, conventional meaning

ϖ Longitude of Periapsis

τ Epoch (time)

φ Azimuth

9 Astronomical Symbols

Bodies

☉ Sol

☿ Mercury

♀ Venus

♁ Earth

☽ Luna

♂ Mars

♃ Jupiter

♄ Saturn

♅ Uranus

♆ Neptune

♇ Pluto

Vectors

♈ Vernal equinox

Chapter 5

Metainfo

1 Copyright

The game, plus all its rulebooks, source files, and other tools can be downloaded gratis at: github.com/Zanderwohl/ExoticMatters.

This book was written by Alexander Lowry. It is typeset in LaTeX.

1.1 Licensing

Implications

This section is not legal advice and does not replace the license. It is provided to enumerate a handful of suggested uses for this book that, in the authors' amateur opinion, are appropriate:

You may use Exotic Matters for:

- GMing for a private group for free
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- GMing at a convention for pay
- GMing for a private group for pay
- Actual Play podcasts and livestreams
- Modification for a different game experience
- Vivisection for use of parts in other systems
- Piloting real starships[1]

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The authors ask that you would attribute credit to them, just as they have attributed credit to the works and systems that inspired the creation of this game.

The source LaTeX files can be found at github.com/Zanderwohl/ExoticMattersand downloaded gratis, just like the rest of the game.

2 Further Reading

TTRPGs

Apollo 47 by Tim Hutchings (Personal Website: thousandyearoldvampire.com). A lightweight RPG containing a 23-page play manual, and 1177 pages of NASA manuals from the Apollo era. A veritable tome of beautiful technical manuals, this RPG actually plays pretty simply in the ebb and flow of mundane and hypnotic technobabble.

[1]Do note the disclaimer concerning *fitness for a particular purpose...*

Forgotten Futures by Marcus L. Rowland. "The Scientific Romance Role Playing Game" celebrates science fiction of the late nineteenth and early twentieth centuries — the likes of Jules Verne and Georges Méliès: The dream of steam and electricity to bring new flourishing. Built of "discarded possibilities; the futures that could never have been, and the pasts that might of led to them", this system is full of wonder.

Lasers and Feelings by John Harper (Twitter: @john_ harper). This is a very lightweight RPG system that fits on a single page; its lasers and feelings axis inspired the creation of this game, after the author played nearly an entire Apocalypse World campaign without rolling on about half their moves more than a couple times.

Courses and Lectures

AERO3240 - Orbital Mechanics by Steve Ulrich, PhD, PEng *Associate Professor, Department of Mechanical and Aerospace Engineering and Director of Spacecraft Robotics and Control Laboratory*, Carleton University of Ottawa, Ontario, Canada, Earth. Lectures are available for free online.

Physics, Mathematics, and Engineering

Fundamentals of Astrodynamics Second Edition by Roger R. Bate, Donald D. Mueller, Jerry E. White, and William W. Saylor. Excellent book on the basic physics of spaceflight.

Introduction to Space Dynamics by William Tyrrell Thomson. Instructional textbook on the physics concepts directly relating to a spacecraft.

History and Art Books

A History of Space Exploration by Tim Furness. A History of manned and unmanned rockets from Goddard to the late 90s, giving an overview of the numerous early spaceshot attempts, as well as ambitious plans and concept borne of those hopeful space programs.

Imagining Space by Roger D. Lanius and Howard E. McCurdy. A gorgeous book about the future dreams of spaceflight from different eras. Contains many beautiful pieces of concept art depicting the most ambitious dreams of space pioneers. Also includes detailed analysis of the varied imagined futures, and how they reflect the times of their progenitors.

Fiction

Arena by Fredric Brown. A first-contact story where a man wakes up in an invisible arena, facing off against a bizzare rolling alien, whom he must fight to the death.

Inspiration for *Star Trek* episode of the same name.

Citizen of the Galaxy by Robert Heinlein. A young slave boy is taken in by space traders after his adoptive father is executed for being a spy. He travels between many strange and incomprehensible cultures before arriving on the planet whose culture to him is strangest of all - Earth.

The Cold Equations by Tom Godwin. A stowaway is discovered aboard an emergency vessel. Without enough fuel to land with the extra mass, the pilot must jettison the stowaway, or else face a certain crash.

Destination Moon 1950 film. George Pal film (with Robert Heinlein as a writer) often credited with inspiring viewers with a plausable depiction of a human moon landing. The first film to consider the engineering and science behind a real moon landing.

The Dispossessed by Ursula K. Le Guin. A young physicist discovers laws of the universe allowing for vastly more powerful and quick space travel. Vaulted to fame, he is caught between his anarchist — but poor — home planet and its rich, opulent capitalist neighbor-planet on the verge of revolution.

First Contact by Murray Leinster. An Earth ship encounters an alien ship of roughly equal technological power. While both ships want to establish peaceful contact and trade of ideas, neither wants to muster unfounded trust first. Includes one of the earliest instances of a "Universal Translator".

The Forbidden Planet 1956 film. An early sci-fi movie which Gene Roddenberry credited for inspiring Star Trek. Notable for being the first film to depict a human-built FTL ship, the first to be set entirely on a planet other than Earth, and among the first to feature a robot as a character with some personality. Features a totally invisible monster whose motivations have become a classic sci-fi twist. Also has a classic "father and daughter alone on a desert planet with secrets to hide and maybe they'll murder people to keep it that way" which is another fun one.

The Left Hand of Darkness by Ursula K. Le Guin. An envoy for humanity is sent to a planet known as Winter to establish first contact. He finds a strange species of human that is biologically androgynous, and free of gender, causing him to reexamine assumptions he has made about his culture and himself. This story inspired the strange types of humanoid aliens found in this game.

A Martian Odyssey by Stanley G. Weinbaum. A 1933 short story featuring detailed landscapes and aliens with scientifically-backed biology. Considered the first story to feature an alien that exists as more than a companion or enemy for the hero, but as an independent being of high intelligence with incomprehensible emotions and motivations. Also includes a silicon-based lifeform that "breathes" silicon-dioxide waste as bricks, with which it slowly builds a pyramid.

The Moon is a Harsh Mistress by Robert Heinlein. The moon, a former prison colony for Earth, grows restless at the poor treatment of 'loonies' by Earth. They start a rebellion, opting to lob rocks at Earth via an enormous railgun, which impact the surface like atom bombs thanks to the gravity well. Shows an enormous complex of computers becoming sentient emergently, who is probably the most interesting character in the book. Also features the sex-fantasies-disguised-as-culture endemic to Heinlein's adult novels.

The Mote in God's Eye by Larry Niven and Jerry Pournelle. Humanity makes first contact with aliens of a strange culture with confusing values and a caste system which seems unjust to human sensibilities. Slowly examining the geology, artefacts, and sociology of this culture reveals the dark secret of this civilization's history over the eons.

The Rolling Stones by Robert Heinlein. A set of genius twins decide to use the money they made from an invention to buy a ship and wander the solar system. Unfortunately for them, their family wants to tag along. Likely influenced the Star Trek episode *The Trouble with Tribbles* (for which Heinlein asked no licensing fee but only a signed copy of the *Star Trek* script).

Space Cadet by Robert Heinlein. A boarding-school story set in space. A handful of space cadets find themselves on their own when asked to investigate some strange occurrences on Venus. Features a flight computer controlled by gears, where a cam must be cut for each planet according to its gravity and atmosphere, to correctly control automatic landing.

Star Trek: The Original Series 1966 television series. One of the early science fiction television serials, Star Trek has both fun concepts and a healthy helping of ham. About half the episodes are watchable to a modern viewer without a literary background. The episodic format of unusual creature encounters, as well as the existence of space colonies from before the invention of lightspeed that were forgotten may have come to Exotic Matters from this series.

Thunderbirds 1965 Television series. Follows the heroics of a secret rescue agency, and their advanced rescue vehicles. Gorgeous Midcentury Modern design.

The Word for World is Forest by Ursula K. Le Guin. A colonizing force from Earth enslaves the tree-dwelling natives of a forest planet, Athshe, inflicting cruelties as they harvest the rarest of resources in the galaxy from the lush planet — trees. Abandoning their laws against violence, the Athsheans rise against their human oppressors to save their home.

Software

Flight of Nova Indie spaceflight game with responsive and intuitive flying controls as well as realistic Newtonian orbital mechanics.

Kerbal Space Program A substantial spaceflight simulator game in which players build slipshod and tinkered-together rockets to launch "Little Green Men" into orbit, to their planet's moons, and into the solar system beyond. Well-balanced between gentle entry-level gameplay and a high skill ceiling.

Space Engine Home desktop planetarium software that includes most known objects in the universe in stunning detail. Fills the rest of the universe with procedural content extrapolated from scientific principles. One of the better ways to understand the existential terror of the size of the universe.

3 Ethics

Though this game is licensed with very permissive conditions, the authors ask you to abide by certain ethical guidelines. Think of the following as a nonbinding, informal, good-faith, agreement to be a chill person.

Please play the game under the condition that:

1. the game be used only for good, not evil.
2. the identities of all players (gender, ethnicity, medical health, mental health, disability, age, intelligence, sexuality) be respected.

...and that if you wish to not abide by these guidelines, you discontinue play of this game. Additionally, absolutely no fascists are allowed to play this game. This game automatically disincludes fascists, and all fascist ideologies.

4 Image Attributions

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Cover Image *Orion Vehicle Design* from *Nuclear Pulse Space Vehicle Operational Study, Volume III – Conceptual Vehicle Designs and Operational Systems,* 1964

Fig. 4.4 by JensVyff on Wikipedia. https://commons.wikimedia.org/wiki/File:TypesOfConicSections.jp CC-BY-4.0, image changed to grayscale.

Fig. 4.5 by Tfr000 on Wikipedia. CC-BY-4.0, image changed to grayscale.

Appendix A

Using a Calculator

Graphing calculators become incalculably useful when reckoning trajectories. Some problems can be solved analytically and exactly, like position at time, while others can only be estimated, like the area under an arbitrary curve. While not written for any one calculator, most graphing calculators share much functionality. Check with your calculator's manual for specifics on adapting these techniques to your machine.

1 Conics

Most graphing calculators can graph in polar coordinates, and more expensive models may even support spherical coordinates. These modes allow easy graphing of the generic conic equation. While some calculators are programmed with a conics mode, these modes often separate conics by type; circles, ellipses, parabola, and hyperbola may require choosing based on the eccentricity.

Appendix B

Space Glossary

A glossary of spaceflight terms used in this book and other reference materials.

Ballistic Unpowered movement, only affected by gravity. *Sir Isaac Newton in the driver's seat.*

Body An object, or collection of objects considered as one in a physical system.

C The constant representing the speed of light. Also the speed of all massless objects, as well as causality. The speed of light is apparently C from every *reference frame*.

Delta-V Delta means *change in*, and V stands for *Velocity*. The change in volocity, used to describe the cost of maneuvers without terms of fuel weight. Symbolized by ΔV.

Escape Velocity The velocity at which an object will escape the gravitational influence of a body and not fall down again.

FTL Faster than light, the speed 'C'. See also *C*.

Finagle's Law A corollary of Murphy's Law and the Second Law of Thermodynamics: "The perversity of the Universe tends towards a maximum."

Fine Structure Constant $\approx \frac{1}{137}$. Look out for 137.

First Cosmic Velocity See *Orbital Velocity*.

Frame of Reference There are no absolute coordinates, nor absolutely stationary velocity in the universe, so all motion must be measured relative to another object. Such a coordinate system relative to an object is a frame of reference.

Geostationary Orbit A special case of the *geosynchronous orbit* with zero degrees of *inclination* relative to the body's equator. This means the satellite appears to always be exactly stationary in the sky, always above exactly one point on the planet.

Geosynchronous Orbit An orbit whose period is one *sidereal day* of the body it orbits. This means the satellite will travel the same path over the surface of the body every day.

Hyperbolic A trajectory fast enough to escape the gravitational influence of a body will be shaped like a hyperbola. Refers to leaving the local body entirely.

In-Situ In-situation. As opposed to trivial or academic consideration, in-situ describes a case where the discussion is immediately applicable to the present circumstances.

Inclination We do not use inclination in Exotic Matters, don't even think about it.

Inertial Reference Frame A *reference frame* where inertia is maintained. For example, the interior of a spaceship in orbit or the interior of an elevator in freefall, as measured from the elevator's floor.

Luna Earth's largest natural satellite – 'The' Moon.

NAFAL Not as fast as light. e.g. Every object with mass in our universe. See also *FTL*.

Non-Inertial Reference Frame A *reference frame* where inertia is not maintained, i.e. objects accelerate 'on their own'. For example, a reference frame as measured from the surface of the Earth will have objects accelerating downward with no apparent cause.

Orbital Velocity The velocity at which an object will orbit a body, not falling down to the ground.

Parabolic A *suborbital* trajectory from the surface like a cannonball shot or baseball toss.

Reference Frame See *Frame of Reference*

Satellite Generic term for any body orbiting another body. Satellites can be natural planets, moons, asteroids, etc. or artificial craft, probes, or debris.

Second Cosmic Velocity The *escape velocity* from a planet's gravitational field.

Sidereal Day A body's sidereal day is the period of rotation of a body as measured against the seemingly-fixed stars. Because a body orbits another body, the sidereal rotation period is usually slightly shorter than the *synodic day* – Earth's sidereal day is nearly four minutes shorter than its synodic day. Luna's sidereal day is equal to its sidereal month, being tidally-locked to earth.

Sidereal Rotation Period See *Sidereal Day*.

Solar Day See *Synodic Day*.

Sphere of Influence An abstraction to describe the three-dimensional space around a gravitational body where that body's gravity is the overwhelming force. In patched conics physics, only one gravitational pull is reckoned at once; that of the body whose *sphere of influence* the satellite is in.

Suborbital A trajectory too slow or in the wrong direction to complete a full orbit (i.e. eventually hitting the ground).

Synodic Day The rotation period of a body in reference to its parent body; that is, the 'sun' of a planet reaching the same point in the sky on the next day. The angular motion of the body around its parent will slowly cause the parent body to move relative to the celestial background, thus making a synodic day slightly different in length from the *Sidereal Day* if the body is not tidally-locked to its parent.

Tanj There Ain't No Justice.

Third Cosmic Velocity The *escape velocity* from a solar system's gravitational field.

Tidal Lock A body is tidally-locked to its parent if one side always faces the parent. For instance, Luna is tidally-locked to Earth. This occurs because the nearer side of the child body is pulled more strongly on the side nearer to the parent.

Torch Ship An ship that conforms to classical mechanics, but whose power output, thrust, or efficiency are well beyond current or near-future engineering capabilities. Unrealistic, but realistic.

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