Contents

Chapter 1

Life emerges...

Narrator For a long while, there was only darkness. Well, mostly darkness. Photons are to the Universe what microorganisms are to the world. In a nutshell, that stuff is *everywhere*.[1]

1.1 Hello World

Narrator But on a very fateful day, everything changed. Cosmic Dawn emerges with a roar. An especially massive Giant Molecular Cloud is in the final stages of contracting; the internal pressure from within, provided by the random motions of her constituent atoms and molecules, guides the hand of gravity to re-shape her into a critical new state. Over-dense knots and filaments begin to form within her belly. The knots continue to coalesce, becoming ever hotter and denser. Until, finally, new life emerges. Deep within one such dense knot, the protostar Maiais born!
Narrator With her birth, comes Dawn. Protostars spew out photons at a thunderous pace; enough to dwarf an unfathomable mound of radioactive waste. Seven siblings, all due to be born within the narrow window of a million years. Their Mother, Pleione, a particularly compelling Giant Molecular Cloud, now begins her journey through Motherhood. But it's not yet over; she's still in the process of yielding to gravity's nurturing might, slowly contracting and compressing, forming over-dense filaments and birthing new stars within her bossom.

[1] Photons are particles of light. They travel freely through vacuum at a speed of about 299792458 meters per second or 299792 kilometers per second or, if you prefer, 671000000 miles per hour; basically photons travel an unfathomable distance each and every second. Photons are defined according to their energy or, equivalently, wavelength or frequency. The spectrum of energies characterizing photons is called the electromagnetic (EM) spectrum. Photons are produced in the cores of stars, eventually working their way up to escape from the surface. These photons, often mostly from the visible portion of the EM spectrum, are transparent to the Earth's atmosphere. They are detected by our eyes, revealing a wonderfully brilliant and colorful night sky on Earth.

Maia Hello to you, Mother![2]
Pleione Hello to you as well, my child. My young new protostar!
Maia Wow! The Universe is so amazing and pretty. Are all those twinkling things off in the distance other protostars, like me?
Pleione Mostly no, child. Stars live long lives, and the protostellar phase does not last long; only a few million years. Most of the far off stars you are looking at are much older than you. Stars spew out light at a colossal rate, and this is how you are able to see them. Light makes stars twinkle.
Maia Long lives... I'll take it! Whoa, if you look closely at some of those distant stars, they appear to be arranged in interesting ways that make them resemble familiar shapes. Like, over there, I see three stars are close together that form a straight line.
Pleione That is Orion's Belt. Good eye! If you take a larger look at him, you will notice as well a torso, arms and legs.
Maia I think I see them... Wait what are arms and legs?
Pleione Orion the Hunter is in the form of a human. I would describe humans as resembling deformed stars; they look similar, and come in various colors and sizes. But they also come along with many protuberances, such as arms and legs, each with their own set of functions. Orion is but one example of the many stories depicted in the night sky, assigned by that species. Humans dub these familiar stellar configurations "constellations", and they are meant to tell some important story about their history. Humans have developed many stories to explain their origins.
Maia Have you ever seen one?
Pleione One what?
Maia A human.
Pleione Oh! Yes, once, quite some time back. Awful, vile species. Constantly shooting projectiles off the surface of their tiny planet, littering outer space with their garbage.
Maia Yuck. That does sound gross.
Pleione Did you know that Orion the Hunter even has a bow to fire arrows at his enemies?! If you look closely, you can see he is holding it in his left hand, and it forms a large arc in the sky.
Maia I see it!... Wait... Enemies? What kinds of enemies?
Pleione Well, if you follow Orion's Belt from left to right, you will pretty quickly notice a very bright red star. That is the star Aldebarran[3], the Eye of Taurus the Bull. According to the myth, Orion the Hunter fought Taurus the Bull to save the Seven Sisters.
Maia Wow, that sounds very dramatic.

[2]Stars of course cannot speak. But they can communicate with each other, even over very large distances. They communicate by modulating their luminosities on short timescales, brightening and dimming, brightening and dimming, in whatever cadence properly communicates their intended message. Humans are unable to speak, write or even read the language of the stars. Throughout this book, all communications between stars will be expressed in English.
[3]Describe what kind of star is Aldebaran...a red giant?

Pleione I suppose it was.
Narrator Pleione was growing weary. Each of her children emits a wind of charged particles and photons escaping wildly from their surface; $> 10^{38}$ bats out of Hell every second.[4] As the winds collide with the loving embrace of their Mother, they provide an outward pressure and she begins to disperse. The birth of Maiahad initiated the demise of her mother.
Maia Wait, Mother, where are you going?
Narrator Maia, the second most massive of her soon-to-be-born siblings, wears a worried expression upon her face that begets deep concern for her apparently fleeting Mother.
Pleione Oh, young one. There is nothing to worry about. I will be with you always, no matter what adventures befall you.
Maia That sounds suspiciously like a goodbye...
Pleione Shhhh, little one. You are only just now born and still contracting, as gravity continues to find its balance with the fires that now rage within you. Hydrostatic equilibrium awaits.[5]
Maia Um... You're leaving me with a complicated technical term...? What does that even mean?
Pleione It means that the energy produced within your belly must be sufficiently strong to balance the inward forces of gravity, to ensure stability. Take care of your siblings for me.
Narrator Maiaand Pleionecontinue their conversation, Pleionedoing her best to prepare her child for her inevitable journey through the Galaxy.
Narrator Shortly later, one of Maia's siblings awakens. Electra emits a long, sleepy yawn.
Pleione Behold! Your sister awakens!
Electra Uh... Hi.
Maia She *is* super shiny. It hurts my eyes if I stare right at her... Wait, *is* this hurting my eyes? Like, could I go blind?
Pleione Only if you look directly at her.[6]
Maia But I already did that!
Pleione Are you blind?

[4] This estimate comes from assuming that every photon escaping from the surface of the Sun has an energy of 12.86 Mev, corresponding to the highest energy photons produced at the end of the proton-proton-chain (thus our estimate here for the total number of photons should be regarded as a strict lower limit), which is the nuclear reaction process resonsible for converting hydrogen in to helium. We adopt a solar luminosity of 3.828×10^{26} J s^{-1} for this calculation.

[5] Hydrostatic equilibrium is what ultimately decides the size or radius of a star. The term refers to the balance between the outward pressure supplied by the energy released in the core via nucelar reactions (e.g., the proton-proton-chain, which is what burns hydrogen into helium) and the inward pull of gravity.

[6] Stars emit light spanning a wide range of energies. The shielding effects of the Earth's atmosphere protect human eyes from very high-energy photons that would otherwise contribute to the degradation of the human eye. From the surface of the Earth, we only see those photons within the visible portion of the electromagnetic spectrum. But from space, our eyes would not be protected. If stars' eyes are also sensitive to high-energy photons, then looking directly at other stars, especially very close ones, is anything but a good idea.

Maia I don't think so.
Pleione How can you be sure?
Maia Well, I can see you wincing, for one thing. You are looking at me as if I just got in to a fight with a much more massive star and lost.
Pleione Uh... I'm sure you'll be fine. Plus, it could have been worse. It could have been a black hole! They pack a far greater punch than any star, let me tell you.
Maia That was less than convincing. Wait, what is a "black hole"?[7]
Pleione Let's save that one for another day, child. You've already had quite an eventful one.
Narrator Pleione's gas tendrils, swirling and coalescing around her birthing children, gently touching and massaging their young faces, continues to dissipate, faster and faster with the birth of each new star.
Narrator Electra interrupts them suddenly, belching loudly. Plasma is ejected from her surface, emanating from above the equator.
Narrator Her daughters now all born and slowly coming to life, Pleione's time has arrived. Pleione bestows one last kiss upon her daughters, before floating off and dispersing in to the infinite vacuum.
Electra It looks to be a lovely day we have on our hands here. ...I feel as though I just missed something important. Please do fill me in at your earliest convenience. Wait, what are those two whispering about?
Narrator Both Maia and Electra turn their gaze toward Taygete and Alcyone , who together form a compact binary star system.[8] Gravitationally bound, the sisters orbit their mutual center of mass in harmony. Needless to say, they were close. Taygete and Alcyone quietly conferred about the topic at hand, namely which of the two of them is brightest.
Taygete I think it goes without saying that I am brighter than you are.
Alcyone Dream on! I outshine you for sure.
Taygete Alright, tough stuff. Want to know how I know that I am brighter than you are?

[7] A good question. We will learn a great deal about black holes over the course of this book. For now, let us suffice it to say that many black holes are simply dead stars. Their progenitor stars ran out of nuclear fuel, which provided the star with the outward pressure it needed to resist gravity's inward pulling might. With no source of outward-directed pressure, gravity won and the progenitor star collapsed to form a new, much denser object. If the progenitor star was sufficiently massive, it would have collapsed to form a black hole. From death, comes new life. Black holes are so dense that the strength of gravity forbids the escape of light from their interiors. Thus, they are black, and do not emit light. They are only detectable by humans indirectly, via their gravitational influence on surrounding matter and stars. Of course, this only applies to low-mass black holes, comparable in total mass to massive stars. The origins of super-massive black holes, on the other hand, are thought to be much more complicated, and to this day remain shrouded in mystery...

[8] Two objects are said to be gravitationally bound if their total relative energy (i.e., the sum of their kinetic and potential energies) is negative. In this case, the objects orbit their mutual center of mass, carving out circular or elliptic trajectories in a plane. The Earth is gravitationally bound to the Sun, as is the moon to the Earth. Technically, the moon is also gravitationally bopund to the Sun. But gravity gets weaker with increasing distance, and the moon is close enough to the Earth and far enough away from the Sun that it orbits the former instead of the latter, at least directly.

Alcyone Sure. Amuse me.
Taygete I'm definitely fatter than you are, and bigger. Both contribute to making me brighter, relative to *you*. At least, I'm pretty sure that is how it works... [9]
Alcyone Oh shut up... You are neither fatter nor bigger than I am. You *are* way more delusional than I am though. I'll give you that.
Narrator Taygete and Alcyone begin flailing at each other violently, intent on a fight. But they lie outside of each other's grasp, unable to reach with even the longest tendril of plasma either can muster; a sisters' quarrel unrealized. Their efforts futile, they quickly give up.
Narrator Taygete and Alcyone are in fact two members of a triplet. The third companion, Celaeno, lies much farther away than the other two, and is often ridiculed by her fellow twins because of it. But this distance is absolutely necessary to ensure the long-term dynamical stability of the triple; if the inner pair becomes too wide, the gravity exerted by the outer object will pull them apart. Chaos will ensue. All Hell will break loose. This chaos can mediate the ejection of one or more stars from the triple, and even direct collisions. The triplets' current configuration, hierarchical[10] and dynamically stable, is nothing short of fate; binding them to each other practically indefinitely.
Maia Well, I think you are almost certainly identical twins. I cannot see any real difference between you. I mean, look at *Celaeno* over there; she's blue, whereas the two of you are clearly more of a yellow color. She's also *much* fatter and bigger than the two of you combined.
Celaeno Alright, I see your point.
Taygete Agreed. Alcyone, I'd extend a hand in offer of peace, but I don't have one.
Narrator Meanwhile, Celaeno had grabbed her midsection and was inspecting it meticulously. Yep, fatter. Unsure as to whether or not this was a good thing, Celaeno wore a pensive expression, clearly trying to work it out in her head. She was distracted from this self-introspection when she noticed a dense whisp of **Pleione** passing between her and her twin sisters.
Celaeno What's that?
Maia The fleeting remains of our Mother, I am afraid.
Electra That's *Mom*?!
Maia Well, what's left of her.
Narrator The siblings continued to accrete mass from what remained of their Mother, Pleione. They each grew and grew, until eventually they reached a

---

[9] The luminosity of a star increases steeply with both increasing mass and radius. This is the case during the main-sequence phase of a star's life, during which time stars are burning hydrogen into helium in their cores. All stars, once finished with the protostellar phase, become main-sequence stars.

[10] The easiest way to explain a "hierarchy" in a triplet is if two of the stars form a very compact binary, and the third star orbits at a very large distance from this compact pair. In such a scenario, the inner compact binary can be regarded as a single star from the point of view of the outer triple companion, for all practical purposes. Said another way, when it comes to a hierarchical triple star system, there are two orbits with almost opposing properties; the inner binary is compact, whereas the outer triple is on a very wide orbit.

steady-state configuration[11]; this marked the end of their growth, and ultimately the end of the protostellar phase of their lives. In the end, the outward pressure produced from within due to the thermonuclear reactions brewing in their bellies had grown sufficiently strong to balance the inward pull of gravity. Hydrostatic equilibrium achieved! With this balance in place, the siblings would endure most of their lives in this approximate steady-state configuration, slowly fusing the lowest mass nucleon (hydrogen) into the next best thing (helium).

Narrator Sterope came to life suddenly, announcing her appearance with a high-pitched scream.

Sterope AAAAAAAHHHHHHhhhh!!!!! What the Hell, man? Where am I? What am I? When...? You get the idea.

Maia It's okay, sister. You are one of us. We are stars born of the gas and dust of our Mother, a particularly glamorous Giant Molecular Cloud, if I do say so. She has left us now, but not without first bestowing her deepest gift upon us all, along with all of her love.

Sterope Uh... You are all my sisters? We are a family?

Maia Yes!

Sterope In that case, there remains a slim chance that the rest of this conversation will proceed without me feeling the need to scream again.

Maia Progress!

Sterope Uh, yeah, right. Progress. Alright, let's get down to brass tacks. Who are all you strangers? My sisters, I have gathered, but what else? Wait, who am I? More importantly, *what* am I...? I'm starting to feel another scream coming on...

Maia Relax, young one. You're in good company here. Familiar company. *Familial* company, even. We are your siblings and we are stars. Thus and therefore, you too are a star.

Sterope Uh...Okay, but what the Hell is a star? And is that why I am feeling so bloated?

Alcyone I wasn't going to say anything, Sterope, but you do look a little red in the face. Is everything okay over there? Oh...Wait, you asked a good question. What the hell is a star, anyways?

Maia We are born of our Mother. Plain and simple. We formed out of the gas and dust she left behind, after gravity coalesced us into the beautiful burning spheres of hydrogen you see before you. Inside, we home a nuclear furnace that generates energy and emits light. Our insides are so hot, that hydrogen is converted in to helium, releasing photons and hence energy in the process. The hydrogen is our food! Outside, gravity pushes inward, but it cannot surpass the outward push provided by our internal metabolisms. Protostars will continue to contract in to a denser state with a hotter core, until a critical balance is achieved, called hydrostratic equilibrium. This will also get rid of the reddish hue you currently find yourself with, Sterope.[12]

[11] The term "steady-state" implies that the stars are losing mass as fast as they are accreting it.

[12] EXPLAIN BLACKBODY. EXPLAIN WIEN'S LAW AND THE RELATIONSHIP BETWEEN COLOR AND TEMPERATURE.

Sterope Well, that's a relief: the bloating is only temporary.

Alcyone Okay, I think I am following what you are saying... So far. What do we need to eat to keep ourselves going? I mean, we must need energy?

Maia You have plenty of energy to keep you going for billions of years! It's a gift, just enjoy it. You're consuming the hydrogen you were born with; converting it in to helium right there in your belly. The consequence of this act of consuming is that you shine very bright. Photons are emitted every time four hydrogen atoms arec consumed to produce helium, and they leak through your body and emanate from your surface. Bright as a light! The nuclear fuel already stored within you is sufficient to last millions, even billions of years. You'll be shinning practically forever!

Celaeno Sounds to me like an awful lot of time to kill...

Maia There will be plenty of adventures along the way to keep you distracted, I have no doubt.

Sterope Like what?

Maia Only time will tell. But each star inevitably follows its own path through the Cosmos, and realizes its own fate. We are individuals, after all.

Sterope Maia, how do you know so much?

Maia Uh... Well, I don't really. I know what Mother told me. I am the oldest of us, after all, and she explained as much as she could to me before dispersing.

En espanol: Uh... Bueno, en realidad no. Sé lo que me dijo mamá. Soy el mayor de nosotros, después de todo, y ella me explicó todo lo que pudo antes de dispersarse.

Sterope I'm grateful for your efforts. Mother dispersed so quickly, it must have been hard for her to convey a lot of detailed information to you before dispersing so completely.

Maia Uh, yeah. It was. She spoke really fast.

Sterope And you remembered all of it?

Maia Yep. No problem!

Sterope Reeeeaaaaalllly, Maia? Really?

Maia *Sigh.* FINE! Mother only told me a few things. I don't want anybody to panic, so I'm trying to convey that Mother left me feeling confident, like we are more than capable of figuring it out for ourselves.

Sterope Okay, fair enough. It sounds like you are doing your best.

Maia Get off my back, man! I'm trying to motivate the lot of you, make you feel loved, important, etc. Look, you get the idea.

Narrator Maia's shoulders slumped as she let out a prolonged sigh.

Sterope It's okay, Maia. We know. We love you too.

Narrator Steropeblows a kiss to Maia, a warm smile on her face. Maia smiles back, relieved.

Narrator Alcyone belches loudly.

Sterope Alcyone!

Alcyone I'm sorry! It was an accident. The magnetic field lines are churning and wrapping around themselves inside my belly. They keep breaking out

and reconnecting, as if of their own free will.[13] I'm learning that spontaneous emissions are, unfortunately, inevitable. Way out of *my* control, at least.
Narrator Synchronized to the microsecond, Maia and Sterope both roll their eyes.
Maia Just do your best to keep your spontaneous emissions to yourself.
Alcyone Will do.
Electra Uh...Maia, I definitely don't mean to startle you, but some freaky, ominous stuff is going on right behind you.
Maia Your goal there was to *avoid* startling me?
Electra Yep. How'd I do?
Maia Not very well at all. I'm currently terrified of what might be lurking behind me. Okay, I am turning around now...
Narrator Maia turns to see gas and dust had coalesced into a dense knot behind her. She recognized right away the familiar dynamical dance choreographed by gravity; the final stages of the birth of yet another star, another sibling.
Maia Oh, how wonderful! We are witnessing the birth of our seventh sibling. It would seem that Mother is not yet finished.
Narrator Merope came to life with a jolt... and the hiccups.
Merope **Hiccup!** Uh...excuse me. That whole being born thing was a little weird, and **Hiccup!** kind of uncomfortable. It left with me extra gas in my belly, or **Hiccup!** something that has given me the hiccups.
Narrator Meropetakes a minute to relax and compose herself.
Merope Okay. I'm feeling better now.
Sterope Super! I'll try to find solace in your comfort as I struggle to ignore the lingering stench of your quasi-belches... Wait, who are you?
Merope ...Oh right, introductions! I knew I was forgetting something. Hi! I'm Merope!

Merope was the most massive of her siblings, weighing in at a whopping 23 solar masses. Gaseous emissions aside, her presence was hard to ignore amidst the seven sisters.
Maia It's wonderful to meet you, sister. It would seem that you and I form a bound pair. A binary star system! How fortunate that gravity is an attractive force. Our mutual gravitational attraction will keep us in this configuration practically forever... Well, at least until one of us explodes or something.[14]
Merope Wait, what!? Who's exploding?! Is it me!?! I don't want to explode!
Maia Shhhh.... Relax, sister. Nobody is exploding today.
Merope Today!? What about tomorrow?

[13]Most main-sequence stars have magnetic fields that typically emanate from and reconnect at their poles; the younger the star, the more powerful the magnetic field. When two or more magnetic field lines intersect, they "reconnect" to form new, disconnected field lines. This "reconnection" is usually an energetic event, accompanied by a burst of high-energy photons (i.e., gamma rays and x-rays).

[14]The most massive stars end their lives with a dramatic explosion, called a supernova. In one go, the explosion can liberate roughly as much energy as the Sun over its entire 10 billion year lifetime. At their peak, supernovae shine 10^{10} times brighter than the Sun.

Maia Nobody will be exploding tomorrow either.
Merope And the day after that?
Maia Nobody.
Merope And the day after that?
Maia Certainly not.
Merope And the day after...?
Narrator Maiainterjected before Meropecould finish.
Maia Nobody will be exploding for a very long time, if ever.
Merope Okay. It doesn't seem immediately urgent, I guess. But we are *definitely* circling back around to this exploding business at some point...
Maia We will, I am sure. But for the moment it seems we have a family to become acquainted with.
Narrator Maiaturned to address her siblings.
Maia Greetings to you all! I cannot express how happy I am on this day, the day of our mutual births. The stuff that forms our bodies and souls comes from the same Mother, and to her we owe homage! Our existence is blessed by her great sacrifice, having largely spent herself to birth us few. Seven massive siblings, and countless more familial satellites![15] All born of the same stuff, in the same place, and at about the same time. It is truly a time to celebrate. But we are all weary of a prolonged dawn, and should now rest. When we awake, we will celebrate properly!
Merope Count me in!
Electra A party sounds great... *Yawn*...just after I get a little shut eye.
Sterope I could go for a nap, followed by a party. I'm in too.
Narrator Meanwhile, Taygete, Alcyone and Celaeno had fallen asleep, and were snoring loudly. Seven siblings, all born within the narrow window of a million years. Their future looks bright.

1.2 A Gust of Wind...

Narrator Sterope awoke when a gust of wind brushed past her face. The gas was dense enough to temporarily obscure her vision. The wind was sufficiently fast that she could feel it pass by as it caressed her face. All in all, the wind carried enough momentum to startle her out of slumber,[16]. Steropecoughed, clearing the gas from her face. Her surroundings now revealed, Sterope looked

[15] Here, the term satellite refers to any celestial body that is gravitationally bound to, but much less massive than, the seven sisters. Very small stars, brown dwarfs, planets, moons, comets, asteroids, etc.

[16] The momentum an object possesses is defined as the product of the object's mass and its velocity. Momentum is in many ways complementary to the term inertia; momentum quantifies how difficult it is to alter an object's trajectory. The more momentum an object possesses, the larger the total applied force must be (over a given interval of time) in order to change the object's trajectory. More specifically, the total change in momentum can be calculated using the product of the applied force and the total time spent applying that force to the object. The corresponding change in momentum is larger if either the magnitude of the applied force is larger, or the total time spent applying that force is longer.

around, confirming her suspicions; the gas density[17] had decreased substantially since she had fallen asleep.

Sterope My sisters, you must wake up! The remnants of our Mother are leaving us.

Narrator The other six siblings awoke to the scene described by Sterope.

Electra Whoa! What's going on? We're all drifting apart. And where did Mother go?

Maia It's okay, young ones. The last vestiges of Mother have now left us; upon giving birth to us, she activated our metabolisms. We've been spewing light out ever since, in the form of photons. Each photon carries momentum, and transfers some of it to any gas molecule or atom upon collision. Light has been banging in to the gas and dust of our Mother for quite some time now, pushing her outward and away.[18]

Electra Okay, but then why are *we* drifting apart from *each other*?

Maia Mother was made up of gas and dust, which came along with significant *mass*. Now that her mass is gone, it can no longer contribute to the inward pull of gravity.[19] In other words, without our dispersed Mother, between the seven of us we no longer have enough mass in our mutually occupied volume to keep us gravitationally bound. We are now free to drift apart. And drift apart we are destined to do.

Taygete Yeah, yeah, YEAH. But what does all that even *mean*?

Sterope I think it means that this is goodbye... With our Mother's mass now lost, we are no longer gravitationally bound. Relative to each other, we are energetically *unbound*.[20] Fated to wander independently through the Cosmos. Utterly and completely alone. Well, except for Maiaand Merope, I suppose, who form a binary. Oh, and the triplets. Those three are also still gravitationally bound.

Narrator Alcyone's shoulders slump. She begins to cry.

Alcyone Already, I miss each and every one of you.

Taygete Well, at least you have me.

Narrator Alcyonerolls her eyes.

Taygete Hey! I saw that!

Alcyone I'm sorry, sister. You are right. I am grateful for your presence...even if it *is* **all...the...time!**

[17]Density is defined as the total amount of mass per unit volume; lower densities imply less mass for a given unit of 3-D volume.

[18]"Radiation pressure", they call it.

[19]Gravity provides an inward force that keeps particles effectively "glued" together. The strength of this glue is often quantified by something called the gravitational potential energy of the system, which is always negative.

[20]In addition to the gravitational potential energy, particles have relative motions and hence kinetic energies, a positive quantity. The kinetic energy of a given particle is typically quantified by the square of its velocity relative to the system center of mass (multiplied by the particle mass...and, of course, divided by 2). The total system energy is defined as the sum of the kinetic and gravitational potential energies, summed over all particles. If the total system energy is negative, then the system is said to be gravitationally bound, and the particles remain effectively "glued" together.

Maia I'm afraid Alcyoneis right. It is now time for each of us to follow our own paths through the Universe or, equivalently, trajectories through space-time. At least in your case, Taygete , your sister Alcyone will be accompanying you.
Electra Whoa, whoa, whoa! I don't like the sound of this one bit!
Sterope Me neither! Electraand I are going to be completely alone!
Narrator Both Sterope and Electra lock eyes, grasping frantically for one another as they continue to slowly drift further and further apart. Their efforts are wasted.
Maia Do not worry, my fresh new stars. This is all a part of the Circle of Life, just as are you. Something tells me it will not be long before you hear from me again. Keep your eyes peeled to the horizon, and I will soon be there.
Electra Sigh...
Taygete So... Uh... Wow, this is awkward. I guess we'll see you guys later? ...By means of some miraculous and as-yet-to-be-explained mechanism...?
Narrator Taygeteand Alcyonesnicker quietly to themselves, exchanging a glance of mutual understanding. Electra begins to cry. Sterope joins suit. They cry together for a while, before Steropestops and says to her sister, sniffling loudly:
Sterope Do not worry, Electra. It is an exciting time! A new chapter in our lives. What adventures will befall us? What obstacles will we overcome?
Electra How many times will I be overwhelmed by the situation, managing my anxiety by crying and blubbering uncontrollably? I can't wait to find out!
Narrator Despite the brave face, Maia was every bit as terrified as her sisters. The oldest among them, Maiaintently sought to calm her panicking siblings as she slowly drifted from view.
Taygete Well, Alcyone, looks like we're stuck with 'ol Celaeno over there.
Alcyone Yep, looks like it. She was already gravitationally bound to us pretty significantly before the gas left, so I guess it's no surprise that she's still here. Perhaps a disappointment, but not a surprise.
Celaeno Heeeeellllloooo over there! Did you know that I can hear you? I don't want to. But I can.
Taygete Oh, we know.
Narrator Taygeteand Alcyoneexchange a wink of understanding. Celaeno mutters under her breath:
Celaeno I hate you. Both. Profoundly.
Taygete What was that?
Narrator Celaeno speaks louder, so her sisters can hear:
Celaeno I *love* you both. Profoundly.
Alcyone Aw.

Chapter 2

The Triplets...

Narrator Now gravitationally unbound from their siblings, Taygete, Alcyone and Celaeno find themselves drifting off in to the vastness of empty space.

2.1 Two's Company, Three's a Crowd

Narrator Three siblings alone at last. Well, two twins and a target: the inner twins continued to gossip rudely about their outer, omni-present sister.
Taygete She's a little bulbous don't you think?
Alcyone Ha ha. Yeah, you nailed it!
Celaeno I can *still* hear you two. And I am *not* bulbous. A little round perhaps, but never bulbous. And I shine brighter than either one of you. So take that!
Alcyone You may shine brighter than each of us individually, but together *we* outshine *you*.
Taygete Yeah! Take *that*!
Narrator Celaeno lets out a long, exasperated sigh.
Celaeno My sisters, I really don't want to fight with you. First, we're sisters from the same Mother. Second, we're pretty much stuck together in this configuration for the next several hundred million years. So we had might as well make the most of it.
Taygete *Fat* chance, you bulbous sphere!
Alcyone Ah ha, another good one, sister!
Celaeno Well, fine. I guess I'll take a nap then. Better than listening to the two of you...

2.2 The Demise of Taygete and Alcyone

Narrator After some time, Celaeno awoke from a peaceful slumber.
Celaeno Yaaaaawn... What a lovely day, wouldn't you say, Taygete and Alcyone?

Narrator Celaeno turned her gaze toward her sisters, but was horrified by what she saw. Her sisters' relative distance[1] had changed over the course of their slumber. It had gone *down*, in fact. They were now closer than ever before. What's more, it seemed to Celaenothat the relative angle of inclination between the inner orbital plane formed by her sisters's orbital plane and her own outer orbital plane had changed. They were now much more co-planar than before.[2] In fact, currently, Celaeno could only see Alcyone directly; presumably, Taygete was behind Alcyone, her light being eclipsed by the foreground presence of her twin sister, along the line of sight separating her from Celaeno.

Narrator Rather crucially, Taygete and Alcyone now shared a much more eccentric orbit than before.[3] In particular, they now swung out to larger relative distances with respect to their common center of mass; here, they sit patiently due to their much slower orbital velocities [4]. But, they eventually swing to much closer approaches than before, their surfaces almost touching at the point of closest approach[5]. Each time they complete one orbital revolution, the two sisters drift a little bit closer to colliding directly with each. On the whole, there was no mistaking the fact that their orbit was getting more compact...and fast.

Narrator After a particularly close periastron passage, Taygete too began to notice the changes.

Taygete Whoa! What the hell is going on?! I almost just collided with Alcyone!

Alcyone Ah, yeah no kidding! What the hell *is* going on?! Don't get so close to me the next time you pass back around...

Taygete It's not like I am doing it on purpose...

Celaeno Well, don't panic just yet. We need to figure this out, since I can't very well run off to bring back help.

Alcyone Useless to the bitter end...

Celaeno Cram it.

Alcyone Wait... Cram what exactly?

Celaeno Your mouth.

Alcyone With what?

Celaeno Anything that prevents you from talking.

Alcyone I see. You do realize we are floating in the emptiness of an infinite vacuum, right? It's slim pickings I am afraid, at least in so far as cramming materials are concerned.

---

[1] In other words, the distance separating their respective centers of mass.

[2] That is, all three stars orbiting within the same 2-D plane.

[3] The Earth orbits about the Sun on a roughly circular orbit, such that its distance from the Sun does not change much over the course of a year. Hence, a reasonable approximation here for most purposes is that the Earth's orbital eccentricity is nearly zero, or $e \sim 0$. This is not the case for every orbit, however. Some orbits have non-zero eccentricities, orbiting their centers of mass on elliptic orbits. In the limit $e = 1$, the two bodies orbit each along a straight line, and are doomed to crash into each other and collide for negative total orbital energies.

[4] This part of the trajectory of an orbiting body is called "apoastron", and corresponds to where along an eccentric orbit the orbital velocity is at a minimum.

[5] This part of the trajectory of an orbiting body is called "periastron", and corresponds to where along an eccentric orbit the orbital velocity is at a maximum.

Celaeno Right, fair enough. The point is: stop being a jerk. And while you are doing that, I am going to try to figure out a way to save you. I suspect that the shift toward more co-planar orbits is directly related to the increase in your orbital eccentricity. If you think about it, these two things in combination should conserve total angular momentum[6], and might arise if the components of the inner orbit spend more or less time above or below the orbital plane of the outer orbit.[7]
Narrator Celaeno finds herself lost in thought. Several minutes pass. Finally, an epiphany strikes.
Celaeno Wait, I've got it! I know what is going on!
Taygete Super! Well, please do enlighten us.
Celaeno Okay, so our unique three body configuration consists of two orbital planes. You two orbit in one of those planes, and I orbit in another about our mutual center of mass along with the center of mass corresponding to the two of you.
Alcyone You lost me.
Taygete Yeah, what's the point exactly?
Celaeno The point is that your mutual orbital motion is such that its plane spends a net excess amount of time above or below my orbital plane. It depends on our exact configuration, but that's the basic idea. This is critical though, since it means that a net torque is being applied between our orbits.[8]
Alcyone And why should we care about that?
Celaeno Well, unless I miss my guess, this will cause your orbital plane to be torqued toward mine, so that we are in the end orbiting roughly co-planar to each other. Unfortunately, in order to conserve total angular momentum, this also causes the eccentricity of your orbital motion to increase.
Taygete Huh? Say that again? How did you get so smart, anyways?
Celaeno Hmmm...I don't know. We're all different, right?
Alcyone Sure.
Taygete Why not?
Celaeno Okay, let's review. Basically, I suspect that the shift toward more co-planar orbits is directly related to the increase in your orbital eccentricity, which we are clearly seeing. If you think about it, these two things in combination should conserve the total angular momentum of our collective three-body system, and might arise naturally if the components of the inner orbit spend

[6]DEFINE ANGULAR MOMENTUM AND CONSERVATION THEREOF.

[7]Sir Isaac Newton was among the first to consider the mutual gravitational interactions of a hierarchical triple star system. He realized that, if the orbital plane of the inner compact binary is inclined relative to the outer orbit of the tertiary companion, then an asymmetry can arise where the components of the inner binary do not spend equal amounts of time above and below the orbital plane of the tertiary. This provides a net torque on the inner binary, reducing its orbital inclination with respect to the outer tertiary orbital plane. In order to conserve angular momentum, the eccentricity of the inner binary must increase, reaching a maximum when the orbital plane of the inner binary crosses that of the outer tertiary. If the eccentricity gets to be sufficiently high, then the components of the inner binary can collide and merge. For triples that do not undergo a collision in the inner binary, these oscillations in orbital inclination and eccentricity are nowadays called "Lidov-Kozai oscillations".

[8]DEFINE TORQUE!

more time above (or below) the orbital plane of the outer orbit. Apart from that, well, there's not much to say, really. Your mutual periastron approach is already comparable to the sum of your radii. And it is still decreasing due to the aforementioned effect. And we haven't even considered tidal dissipation acting at periastron due to your *extensive* radii being finite, which will only accelerate the rate of dissipation.[9] In short, you're about to collide with each other. In fact, you'll probably merge.
Taygete Wait, WHAT?!
Alcyone WHAT?!
Narrator Just then, Taygete smashes in to Alcyone as they both re-approach their mutual periastron passage. The collision is violent; the relative velocity is of order the sum of their local orbital speed, which is several hundred kilometers per second. Needless to say, the sisters never stood a chance. Their innards and organs (i.e., massive globs of hot gas) are flung violently away from the merging pair. It is a grizzly scene.
Celaeno Oh, Dear Lord! I think I'm going to throw up. SO MUCH PLASMA! Gross, disgusting, and emotionally it's a lot to handle. ...Yep, here comes the vomit...
Narrator Celaeno suddenly vomits, spraying a particularly potent coronal mass ejection (or CME, for short) in to her immediate vicinity. The vomited CME extends in an arc spanning about 120 degrees due to Celaeno's rapid rotation rate.
Celaeno Oooooooh my Gawd, they've got to be dead after that. So gross!
Narrator Celaeno nearly vomits a second time, but manages to stifle the urge.

2.3 From the Ashes...

Celaeno ...Uh...I guess I should check to see if everybody is okay? ...CAN YOU HEAR ME?! ARE YOU STILL THERE?!
Narrator Gravity was in the process of taking the remains of what had once been Taygete and Alcyone, and re-shaping them into a brand new star. Formed from two stellar corpses, this new star was quickly turning out to be nearly twice as massive as each of his individual progenitors. Suddenly, the product of this coalescence awoke.
Lacedaemon Uh...Hello, there! My name is...uh...Lacedaemon, I do believe. I appear to be new to the scene...of which I know absolutely nothing about. Where are we exactly? Uh...*What* are we?
Celaeno Hello! You are my new brother. We are stars; spheres of gas and dust contracting due to gravity into the configuration you see before you, which in turn rose the temperature in our cores *a lot*. We are slowly undergoing nuclear fusion in our bellies, converting hydrogen into helium and in the process emitting energy in the form of light or photons. The outward momentum supplied by

[9] DESCRIBE TIDAL DISSPATION, AND EXPLAIN WHY IT IS MOST RELEVANT AT PERIASTRON AND FOR OBJECTS WITH LARGES RADII.

the photons provides the outward pressure we need to balance the inward force from gravity. Mother called it “hydrostatic equilibrium”.
Lacedaemon Wow, that was a lot of very technical information. Still, I appreciate it very much! In fact, I'm quite impressed. Now that you mention it, I'm starting to feel very balanced overall.
Celaeno I'm glad to hear it!
Lacedaemon ...Well, except for this excess rotation I seem to be holding on to. And it goes right to the belly, let me tell you. Wow, this bulge is really extending outward at my equator. SUPER!
Narrator Lacedaemon rolls his eyes to accentuate the sarcastic remark.
Celaeno Don't worry, I've seen it lots of times before. New stars spin down as they grow out of infancy.[10] So, the “belly” will go away. You'll settle in to a more sphere-like shape in no time. I think the whole thing has something to do with “magnetic fields”, or so I have heard. As near as I can tell, this is some magical force that slows your spin rate down as you mature into a beautiful new star.
Lacedaemon Hey, alright! Good news. I'm sold. I mean, who doesn't appreciate spherical symmetry? Weirdos, that's who. Uh...So now what?
Narrator Celaeno liked her new brother, convinced she would appreciate having him around.
Celaeno We focus on the journey ahead, of course. Who knows where our fate will take us. But now that we are free of our siblings, I suppose almost anything *could* happen. Here is hoping for mostly good things!
Lacedaemon Wow, this is exciting! Do you suppose we will run in to our other siblings?
Celaeno Well, it's a big Galaxy out there, that much is for sure. But, as I said, anything *could* happen, especially given the long lives of stars.
Lacedaemon We have that going for us! Wait...Just how long are we talking about?
Celaeno Many millions or even billions of years. In fact, I am guessing that somewhere out there are stars as old as the Galaxy itself.
Lacedaemon Wow! By the time I'm that old, I hope to have toured the entire Galaxy....Twice!
Celaeno In that case, we had better get started. The Galaxy sure isn't getting any smaller...

[10] ANGULAR MOMENTUM CONSERVATION DISCUSSION, in the context of spin!

Chapter 3

From a Lonely Road, to a Crowded Cluster

Narrator Sterope watched in sadness as her family slowly drifted out of view. A tear made of plasma streamed down the length of her face. Sterope had a lonely road ahead. But, little did she know, her isolation would not last for long.
Narrator She drifted aimlessly through the Cosmos for several tens of thousands of years. The scenery was nice for the most part, since she remained close to the disk of the Milky Way where most stars are currently being born. The nebulae from which they are birthed are often beautiful to behold, illuminated by the light of the stars they birth. A true symphony of color.
Narrator Sterope noticed that she happened to be moving in a very similar direction, with a very similar velocity, to a particularly far off but bright blob she couldn't quite resolve with the naked eye. She could infer a rough distance based on having monitored her relative motion to it, however.[1] It was far away and extended, no doubt about it. Too big to be a star. Too bright to be a few stars or even a gas cloud. So what could it be? That doesn't leave much...
Narrator As the days, weeks, months, years and centuries passed, the far

[1] The term "parallax" refers to a technique used by astronomers to calculate the distances to the nearest objects to the Sun. It is the angular separation on the sky between two independent measurements of an object's angular position, performed from two distinct locations with a large displacement or baseline. The largest possible baseline is given by the motion of the Earth about the Sun, such that the two different measurements of the object's angular position are separated in time by ~ 6 months, and the length of the corresponding baseline is twice the Earth's orbital distance from the Sun. The basic idea behind the concept is most easily conveyed by extending one's arm outward in front, perpendicular to the torso. Extend one finger in to the air and focus on it. Close one eye. Then close the other eye, and open the originally closed eye. Repeat this process. You will notice that your finger appears to suddenly shift positions relative to the background. The scale of this shift depends on the relative distance between your eye and your finger, as well as between your finger and the background. Hence, measuring the size of the angular displacement in degrees or radians can be used to compute the object's distance from the observer. The concept is identical to that underlying stellar parallax. PICTURE OR DIAGRAM?

off blob drifted ever closer, occupying a larger and larger fraction of Sterope's view of the sky. Regardless, the blob eluded resolution for what seemed to Sterope like a very long time. But it continued to draw closer....

3.1 A New Home...?

Narrator One day, Sterope awoke surrounded by stars. There were thousands, perhaps millions, within her immediate view. She suddenly recalled drifting ever closer to something bright and blurry that she had never quite been able to see before falling asleep. If her rough calculations were right, she was about due for a very close encounter with whatever the bright blurry object happened to be. To her surprise, the mysterious object turned out to be a compact very dense cluster of stars; before awakening she had inadvertently wandered right in to the middle of it.[2]

Narrator The denizens of this cluster were typically old (i.e., billions of years in age), but the range of stellar ages was large; clearly, multiple episodes of stellar birth had occurred here at one time or another. All together, a very large number of stars occupied a volume so compact the stellar density reached a million stars per cubic parsec at its center.[3]

Narrator Obviously, traveling through the sparsely populated space of the Galactic field occupied the most time for any traveler, due its vast extent. This is No Man's Land, a sea of now dead star-forming regions long forgotten, exhausted of their gas supplies. Out in the Galactic halo and far from the disk[4] of the Galaxy where most stars are currently being born, only old massive and dense globular clusters exist, fossil records of a very early phase in the formation of the Galaxy. Apart from these, stars are extremely scarce in these barren outer regions of our Galaxy.

Narrator Suddenly, a strange voice interrupts Sterope 's train of thought...

Jane Hello there! I see you are passing through in something of a hurry. ...and there you go again. Bye!

---

[2] As was the case for the Seven Sisters, most, if not all, stars are thought to be born in "clusters", gravitationally-bound and compact groupings of stars, ranging in numbers from a few tens to several million, with central densities in the range 10 $M_\odot$ pc^{-3} - 10^6 $M_\odot$ pc^{-3}. These stars are all thought to form from the same Giant Molecular Cloud, as gravity shaped it into denser knots and filaments, creating the ideal environment for star formation. However, the most massive star clusters, may be the products of the mergers of several lower mass clusters. The answer to this question is still an active area of research.

[3] The field of the Milky Way, or No Man's Land, effectively denotes those regions in our Galaxy outside star clusters, the Galactic disk and its inner, denser central regions. The Galactic field is where the stellar density is at its lowest in Our Galaxy, and the time for light to travel from one star to the next can be many many years. To put it into context, the Sun's nearest neighbor, Proxima Centauri, is located roughly one parsec away (or about 3.26 light years). If you take the Sun and Proxima Centauri and place them in their current configuration in the star cluster currently hosting Sterope, roughly one hundred stars would lie between the pair. Sterope's new home is a globular cluster, the oldest, most massive and densest of all star clusters.

[4] NEEDS A PICTURE, with a "you are here" showing the Sun. Point out the gas, star-forming regions, etc.

Narrator Sterope realized she was moving a little faster than the other stars in the cluster. Suddenly, she whipped past another one.
Gene Hey! Watch where you're going!
Sterope So sorry!
Narrator Sterope glanced back at the scene of the near-collision, grateful for those few kilometers that spared her from a direct collision.
Narrator Sterope turned back around to face her forward motion, only to discover that she was about to collide with yet another star. Frightened, she closed her eyes and hoped for the best.
Louise Whoa! Whoa! WHOA!
Narrator It's a close call. But the pair of stars manage to avoid a direct collision. Instead, Sterope flies past Louise, too fast to say hello.
Narrator As Sterope whips by, her gravitational influence is felt by Louise, and vice versa. Sterope is more massive than the other stars in the cluster, since most are much older than her. When she undergoes a close encounter with a much less massive Louise, momentum conservation dictates that she induces a strong deflection to Louise's trajectory through the cluster.[5] In this case, Louise is flung off and escapes from the cluster, causing Sterope to end up gravitationally bound to it in Louise's stead. Momentum conservation strikes again! Needless to say, Sterope felt terrible.
Louise AAAAAAHHHH!!! Help! I'm floating away!
Sterope I'm *so* sorry! I didn't mean to do it! It was an accident.
Louise Uh...I don't think that helps me. ...Nope, I'm still escaping to infinity. This is all your faaauuullllttt...
Narrator Sterope could barely hear Louise now, as she retreated beyond the outer boundary of their host cluster and in to the empty space beyond, No Man's Land.
Sterope WHAT?! I can't hear you?!?
Narrator Sterope's shoulders slumped. Another one bites the dust. Saddened, she mutters defeatedly:
Sterope I am more sorry than I could ever say. Well... Good luck, I guess.

3.2 Sterope's New Neighbors

Narrator Sterope suddenly realized she was completely surrounded by stars. They were so close she could make out the faces of hundreds, even thousands, of them. This was a little too close for comfort for Sterope , relative to what she had grown accustomed to over the last few million years. In the neighborhood of the Sun, the approximate inter-stellar distance is of order one parsec. Said another way, the distance between the Sun and its next nearest neighbor in the

[5]To remind the reader, the linear momentum of a particular is given by the product of its mass and velocity in 1D. To change a particle's momentum, a net force must be applied for a finite interval of time. Particles with more momentum require either a larger applied force or for a given force to be applied for a longer interval of time in order to significantly change their momentum.

Galaxy, Proxima Centauri, is about one parsec (or about 3.26 light years). Way out in the halo of the Galaxy, the Galactic field, No Man's Land, the inter-star distance drops by many orders of magnitude relative to the Solar neighborhood. Sterope had been traveling for millions of years, a short span of time relative to her expected lifespan, but long enough for her to travel out of the Galactic Disk, and in to the Galactic Halo; a sparse sphere of old stars surrounding the Galactic Disk and Bulge. Here, dense gravitationally-bound bundles of stars, called globular clusters, reside. And not much else.

Narrator Sterope was now in the very core of just such a globular cluster, having inadvertently collided with it while escaping from the Galaxy, via the Galactic Halo. Gravity had acted to focus Sterope's trajectory, drawing her inward toward the million solar mass globular cluster. Within the cluster core, the stellar density was now about a million times higher than in the Solar neighborhood; the average distance separating Sterope from her closest neighbor had gone from about a parsec, to about 1/100's of a parsec.

Narrator Startled and overwhelmed by all the staring faces, Sterope gasped. It sure was a lot of personalities to introduce yourself to, get to know and, let's face it, tolerate. Sterope wasn't so sure she was up for the job.

Enrico Why hello there! I am Enrico, it's nice to meet you.

Narrator Sterope turned suddenly, toward the mysterious voice.

Sterope Uh... Hi! My name is Sterope. If you don't mind me asking, where am I exactly?

Enrico You find yourself in an old star cluster. A globular cluster! Most of the million or so stars spanning the roughly twenty parsecs of our cluster, where its outer reaches can be found, and where stars slowly bleed back in to No Man's Land, were born at more or less the same time as the rest of the older stars in the Galaxy. From the same Mother Cloud. I, on the other hand, am older and come from a different generation of stars.

Sterope All the stars are packed so close together here...

Enrico Yep, it's crammed in here all right. You get used to it pretty quickly though. Mostly you don't notice it. But, every now and then, two stars do smash in to each other. They collide head-on. BOOM! More often though, two stars undergo strong deflections, during which one star passes by another star so closely that their stellar surfaces are almost touching. Of course, if their surfaces don't touch, then instead of colliding they tend to bestow a strong deflection, one to the other. This causes a deflection in each star's trajectory, and can either slow or speed them up.

Sterope Well, which is it? Do they speed up or slow down?

Enrico More massive stars tend to accelerate lower mass stars more easily, for a net gain of linear momentum. Conversely, lower mass stars tend to *be* accelerated by more massive stars such that, by conservation of linear momentum, the more massive perturbers tend to be decelerated. So, in the end, more massive stars tend to be slowed down, whereas lower mass stars tend to be sped up, on average. Not much you can do about any of it, really, except enjoy the show...which by the way, I highly recommend.[6]

Narrator Enrico winks at Sterope, who laughs.

Sterope How old are you...if you don't mind me asking?

Narrator Enrico thinks about the question for a moment...

Enrico How old is the Universe now? Wait...if I remember right, stars older than me used to yammer on about the number 13.7 Gyr for the age of the Universe, give or take a few hundred million years... I think...[7] Does that sound about right to you?

Sterope I guess so, but I don't really know, to be honest. I was not born long ago compared to you; it hasn't even been a billion years since my birth.

Enrico You are a young one! Good luck on all of life's many adventures, child.

Sterope Uh... Thanks?

Narrator Suddenly and without warning, plasma shot out of Enrico's surface, below his equator. A coronal mass ejection![8] An old star, convective cells toiled at Enrico's surface, stirring upward the plasma from deep within his belly. The plasma hit Enrico's photosphere[9] with enough force to escape, drawing on the outward force supplied by nearby magnetic field lines. Another explosion of plasma emerged from Enrico's lower hemisphere, not unlike a volcano erupting.

Enrico My apologies! This old star is at the mercy of surface convection![10]

Sterope Oh, that's quite alright. It could happen to anybody.

Enrico Back to the question at hand. Okay, so if the Universe is a little less than 14 billion years old, that must make me...twelve and a half billion years old? Yep, that's the number! Most of these other stars are more like nine billion years old...give or take a billion years or so. Young pups, and they mostly keep to themselves. I'm sorry if they seem rude but, in fairness, over 90% of this

[6] An important thermodynamics-based analogy can be drawn between star clusters and a gas in a container. The mean velocity of a star can be regarded as a proxy for its temperature: larger mean motions imply hotter temperatures. Since all particles in the system are free to interact and exchange energy (via mostly weak deflections induced by gravity in star clusters, and direct collisions between atoms or molecules in a gas), the system tends to evolve toward a "thermalized" state in which all particles have comparable kinetic energies or temperatures.

[7] All the available empirical data point to and are roughly consistent with this age for the Universe. For example, no star older than this critical upper limit has ever been observed.

[8] A coronal mass ejection (CME) refers to the ejection of plasma from the surface of a star. Large amounts of matter (made up of protons and electrons, mostly) and electromagnetic radiation are launched out into space, and can either remain close to the stellar surface or be flung into the Solar System and beyond. CMEs are known to be associated with very energetic shifts and changes in the star's outer magnetic field and a reorganization of its magnetic field lines.

[9] The photosphere is the outer shell of a star from which light is radiated and emerges.

[10] If a steep enough temperature gradient (i.e., the temperature increases rapidly with increasing distance from the star's center of mass) exists in the interior of a star, an instability can arise in which heated plasma ascends and cooled plasma descends. This can also occur if the gas has a high heat capacity, implying that it cools slowly as it expands. As a bubble of gas ascends, it finds itself in a region of lower pressure, allowing it to expand and cool. The bubble must remain cooler and less dense than its surroundings in order to remain buoyant and continue to ascend. Otherwise, if the bubble cools below the temperature of the new ambient plasma, its density will rise above that of the surrounding plasma and it will lose its buoyancy, sinking back down.

cluster is comprised of their generation, so I guess it's no surprise they mostly keep to themselves.
Sterope Actually, I'm a little relieved. This is a *lot* of stars in a very crammed space. I'm really not used to it, and was worrying how I would even begin getting to know all of these faces.
Enrico Oh, don't worry about that. I'm happy to chat any time you like, and to defer any time you prefer not to. But these others will mostly inter-mingle with their own kind. You'll be lucky if even one of them strikes up a serious conversation with you. I mean, they are polite, I give them that. They just prefer not to engage with outsiders directly, which are very rare around here. You're the first one in well over a billion years!
Sterope Well, I'm perfectly fine with them keeping to themselves for the time being. I think I will do the same... Hmmm... How do you suppose I might find my way out of here?
Enrico You want out, huh? I suppose I cannot blame you. It is crowded in here. But I warn you, accomplishing that feat is anything but easy. Can I ask: Where are you headed in such a hurry?
Sterope Well, nowhere, really. I guess I was just hoping to explore the Galaxy, and maybe even stumble across my missing siblings. We were all born from the same Mother Cloud. Ever since our birth cluster dispersed, I've been a little worried about them. Now though, I'm more than a little worried that it's a really big Galaxy out there, and if they have been traveling as I have, then finding them within my lifespan could be impossible. Still, I have to try![11]
Enrico Well, it sounds to me like you want to make your way back to the Galactic Bulge, which surrounds the central nuclear cluster and a non-negligible fraction of the Galactic Disk. Unless I miss my guess, if you started out in the Galactic Disk somewhere, which is most likely the case for a young pup such as yourself, then your best bet for finding your siblings is in and around that central region of our Galaxy. I know that doesn't narrow it down as much as you'd probably like, but at least it's a start.
Sterope Thank you! I really do appreciate it. Yes, it is a *definite* start. Wait, just one more question: How the heck do I get out of this cluster?
Enrico Oh, right. *That* question. Well, you're not going to like the answer.
Sterope I don't care, try me anyway.
Enrico To do that, you'll need to find not one, but *two* black holes, lurking around somewhere here in the core. I know they are here...somewhere.
Sterope Wait, what's a black hole? And why do I need *two* of them?
Enrico Well, to answer the second question, you need *mass* and *lots of it* confined to a small volume if you want to be able to achieve the acceleration you will need to escape from this cluster. This is a basic requirement in order for gravity to impart the required total force needed to achieve such a high velocity. That is, a sufficiently large gravitational acceleration must be imparted over a given timescale in order to accelerate an object to a final velocity that exceeds

[11] SOMEWHERE IN THE BOOK, INCLUDE A MAP OF THE GALAXY, ALONG WITH ALL SEVEN SIBLINGS' PATHS THROUGHOUT IT!

the local escape velocity of the cluster.[12] Looking at you, I'd guess you're, what, 3 maybe 4 solar masses?
Sterope Whoa whoa WHOA! My appearance is pretty much the last thing I wanted to discuss with you. Besides, I really don't see how my weight is relevant to this discussion...
Enrico Because I have some idea how massive the most massive black holes in this cluster might be, and you need *two* that are each more massive than you. The more massive they are relative to you, the easier it will be for you to achieve the required acceleration.
Sterope Gotcha. Alright, fine. Last time I checked I was...
Narrator Sterope's voice drops to a whisper...
Sterope ...3.3 solar masses or so. Buuuuuut I've burned through a lot of nuclear fuel since the last time I checked, so I think it's probably a bit less than that now.
Enrico Nothing to be ashamed of as far as I am concerned.
Sterope Oh please, what do you weigh? Half a solar mass?
Enrico Nah, more like a quarter of a solar mass, last time I checked.[13]
Sterope I am so jealous right now. Alright, so what are these "black holes" you speak about, and how do we find them?
Enrico Well, I guess the most important thing to know is that they are as dark as they come. They don't shine. At all. So finding them is obviously a pretty serious challenge. As to what they are, technically, they are the corpses of stars once much more massive than yourself, now wandering unseen through the Cosmos.
Sterope Dead stars? Really? So, basically, I am looking for ghosts haunting this cluster, which I rather conveniently cannot see? And what is it you expect me to do with these dark ghosts, once I find them?
Enrico You'll have to capture 'em. Well, actually, first you'll have to convince two of them to partner up and form a bound binary system. Then, you're going to need to convince them to let you take a run at them. You'll have to work out the details on your own, which I warn you are not as straight-forward as you might expect, especially when chaos rears its ugly head and enters the

[12] The local escape velocity is defined as the minimum velocity required at a given distance from the cluster center of mass for the total energy of the escaper to exceed zero or, equivalently, to become gravitationally unbound. A simple way to calculate the local escape velocity, using conservation of energy, is to equate the kinetic energy of an object to its local gravitational binding energy, keeping the object velocity as a free parameter. If you solve this equation for the object velocity, you will obtain the minimum speed needed at that position in the host cluster gravitational potential for the object to become gravitationally unbound and escape to spatial infinity (asymptoting to zero velocity at spatial infinity in the context of this simple idealized equality). PROVIDE EQUATIONS!!!

[13] Stars in the main-sequence phase of lives share a relationship between their total mass and the duration of their lifespan spent on the main-sequence. This relation is such that the most massive MS stars evolve the fastest, and have the shortest lifespans. In fact, the evolution is so slow for the least massive MS stars that those with masses of only a few tenths of a solar mass should have total ages that exceed the current age of the Universe. That is, some of these stars have been burning hydrogen into helium in their cores for over 13 billion years, and they are not yet done!

picture.[14] But, in principle, two black holes bound in a compact binary should have enough binding energy to give you the acceleration you need to escape the cluster.[15]

Sterope Wow, that is a *super* complicated plan. Sigh. Well, I guess I'll have to find a way to make it work, which brings me to my last question: How, in the name of Hell, do I find these black holes?

Enrico There is only one sure fire way, child. You must search for a star orbiting within what appears to be a companion-less binary star system. If the black hole forms a binary star system with another luminous star, *any* luminous star, then it becomes possible to observe a star in orbit about something that cannot be seen. This immediately implies the unseen presence of a dark compact object (i.e., a dead star) binary companion. You can then use the orbital speed of the luminous companion as a function of distance from the unseen black hole to calculate the approximate mass of the black hole. Just measure the time it takes the luminous companion to orbit the black hole once, and measure the distance from the center of mass that the companion appears to be orbiting. The orbit should trace out an ellipse. Calculate the typical orbital velocity by dividing the circumference of this circle by the orbital period.

Sterope Woooooooooow. This sounds like a loooooot of work. I don't know about this... I mean, what are black holes even like? *If* I can find not one, but *two* of them, do you think they will agree to help me escape from this cluster?

Enrico Hmmmm... A fair and good question. Few stars have gotten to really know a black hole and survived to tell the tale, to be honest with you... But they do have one weakness: they have a constant hunger to grow. Perhaps if you have food to offer in exchange for their services, they would be more inclined to help you out.

Sterope So...bribery? You are suggesting that I bribe them?

Narrator Enrico shrugs rather non-chalantly.

Enrico It often works, I have to say.

Sterope With what?

Enrico Uh, well, mass. Any mass will do.

Sterope Okay...Again though, with what?

Enrico Other stars?

Sterope WHAT?! You want me to deliver other stars to these black holes so that they can eat them? And the stars will die?

---

[14] The chaotic three-body problem has evaded a solution for centuries. The reason is simple: small perturbations to the initial conditions compound over time to change the very outcome of the interaction (e.g., which of the three particles is ejected). A well known term for this is the "butterfly effect".

[15] Recall that the binding energy of a binary star defines its internal reservoir of *negative* energy. The more negative the binary binding energy, the closer are the companions (for a given pair of companion masses). Liouville's Theorem tells us that the total volume in phase space is conserved during the time evolution of self-gravitating N-body systems. In practice, what this means is that the more negative the total energy, the more likely it is particles will be accelerated to high velocities. Thus, it is easier for binaries with more binding energy to accelerate interloping single stars to above the local escape velocity of the host star cluster, even deep in the cluster core where the escape velocity is at its highest.

Enrico No! No! I was just saying such a scenario *could* work, at least in principle. But, yes, those stars would surely die. There are other options though! Murder is not the only one. Any mass will do. The more of it you have, the better your position to bargain. You could even trade some of your own mass in exchange for a boost!

Sterope Okay, okay. So the mass could just as easily be the random crud out in No Man's Land?

Enrico I suppose so, yes. Provided somebody could collect it all in to one place.

Sterope So I could even take it from my own belly, or that of some other star? Like, leave them alive, but take a little bit of their mass?

Enrico I think that will work. Good idea!

Sterope Alright. Now we're getting somewhere. ...Wait, how do you suppose I collect mass?

Enrico Off the top of my head, by finding those stars on the verge of evolving off the main-sequence[16] and somehow getting your self close enough to them (i.e., in a binary system) that, when they evolve off the main-sequence and expand to become red giants[17], they transfer the mass in their expanded envelope over to you.

Sterope Uh...Okay, so basically I am going to have to somehow figure out a way to swap myself in to *and* out of at least one normal stellar binary system...in addition to two black hole binaries? Then, I can use the mass of the black holes to accelerate me to above the escape speed from the cluster? Just trying to wrap my head around this. That seems like a lot of work. Hmmmmm... Where do I even begin?

Enrico Well, child, by my calculations, you need to participate in at least ten direct dynamical interactions with other singles or binaries in the cluster. Two things can help with that: increasing your mass, and reducing your velocity relative to the cluster average. Both of these increase the rate of collisions with other stars or binaries in the cluster.[18] The reason is related to something called gravitational focusing. During the encounter, gravity helps out a lot; it serves to focus inward the relative trajectories of two colliding particles, making it so

[16] During the main-sequence (MS), stars are converting hydrogen into helium in their cores. This is their primary source of energy, and makes them shine. The MS is the first phase in the lifetime of a star, right after the protostellar phase. It also tends to be the longest phase in the lifetime of a star, often lasting many hundreds or even thousands of times longer than later phases (e.g., the red giant branch phase).

[17] Red giant branch stars (RGB) are more evolved than MS stars, converting hydrogen into helium outside the core in a shell. During the red giant branch phase, stars can expand by up to a factor of several hundred times their former size on the MS. The outer envelope is only tenuously bound, and can easily be stripped by a binary companion as the star expands.

[18] A simple estimate for the rate of direct collisions between identical single stars in a star cluster, borrowed from chemistry by considering a particle traveling through a uniform gaseous medium, comes from the mean free path (MFP) approximation. Crudely, the MFP can be estimated by dimensional analysis, such that the mean free path l is $l \sim 1/n\sigma$, where n is the mean particle number density and σ is the collisional cross-section (i.e., an area corresponding to the direct overlap of two stars' radii; if a star passes within this area, a collision occurs). If the mean particle velocity is v, then the rate of direct collisions is $\Gamma \sim n\sigma v$ and the mean time between collisions is $\tau \sim 1/\Gamma$.

that they are more likely to collide. Hence, slower incoming singles are more likely to collide directly with a binary due to this gravitational focusing, whereas without gravity it would not occur.[19]
Sterope Okay, got it...I think. So...what do I do now?
Enrico Not much you can do, but wait. Don't worry though, gravity will do all the work for you. It will carry you throughout this cluster, and deliver you close to other stars and binaries. You are most likely to run in to the most massive objects in the cluster first; more massive objects exert the strongest gravitational force and, without even intending to, draw you in from further afar. But massive objects are rare, and low-mass stars make up the vast majority of this old star cluster. Usually the end result of these interactions is only a close approach, but often the encounter will be direct and you will become at least temporarily gravitationally bound to these other objects in the cluster...as you will find out for yourself soon enough!
Narrator Sterope noticed she had been drifting farther away from Enrico . She realized the process would continue, and they would soon part ways.
Sterope I notice I am drifting away from you. I can barely hear you anymore, in fact. Thank you so much, Enrico, for all your help. I'm off to find those two massive black holes!
Enrico Good luck, young one. It will take some time, but I have no doubt you will realize your goal of escaping eventually.
Narrator Sterope began her long journey through the cluster. A sea of faces came in to and faded out of view. One thing quickly became apparent to Sterope about her temporary neighbors: they were highly skilled at avoiding eye contact. So she continued on, mostly in silence, in search of the two massive black holes whose help she sought.

[19]We are typically used to thinking of the collisional cross-section simply as the geometric surface area corresponding to the radii of two particles overlapping at closest approach. That is, if the particle radius is R, n the geometrical cross-section for collision is πR^2. The geometric cross-section can be enhanced when gravity is at work, and its effects in altering the velocities and trajectories of the interacting particles are non-negligible. This new cross-section, called the gravitationally-focused cross-section for collision, can be calculated using conservation of energy and angular momentum. FINISH USING LEONARD OR SPITZER PAPERS.

Chapter 4

Taming the Beast

Narrator Electra 's journey began when she left her birth cluster, heading out of the Galactic Disk. But it wasn't long before a close encounter with a giant molecular cloud, named Aethra , diverted her course. The gravitational pull exerted by the cloud caused a nearly 90° deflection.[1]

4.1 A Change of Course...

Aethra I am so sorry, child. It is often that I under-estimate the strength of my own gravity. It would seem I have diverted your course through the Galaxy.
Electra Oh, that's quite alright. Honestly, it could have happened to anyone.
Aethra It is true, but in this particular case, I have inadvertently diverted your trajectory directly toward the Galactic Center.
Electra Well, that sounds mildly terrifying. I *was* feeling a little anxious about the uncertainty in my new trajectory, and my new ignorance regarding where exactly in this wilderness I will eventually find myself. I'm afraid to even look...
Narrator Turning in the direction of her bulk motion, Electra suddenly realized that, as Aethra had pointed out, her new course through the Galaxy pointed right toward the heart of the Galaxy (i.e., the Galactic Center).[2]
Electra Uh oh... That thing off in the distance looks to be a very dense cluster of stars and gas. It looks to be a messy environment too. Well, much messier than around these parts, at least, since mostly it is empty space punctuated by the odd star.
Aethra That's correct, child. In the Galactic Center, there lives a dense nuclear star cluster, jam-packed with stars spanning all sorts of masses and ages. We are in the field of our Galaxy currently, where the mean stellar density is about 1 star per cubic parsec.[3]

[1] INCLUDE DIAGRAM SHOWING THE EVOLUTION OF THE INTERACTION.
[2] DESCRIBE THE CENTRAL NUCLEAR STAR CLUSTER IN THE MW.
[3] Said another way, the distance separating the infamous Sun and her next nearest neighbor, Proxima Centauri, is about a parsec. But if you take the Sun and Proxima Centauri as they are now, and drop them in to the very central regions of the nuclear cluster at the heart of

Electra Wow! That is dense! I guess I will find out for myself when I get there.

Aethra Rest assured, young one, anything could still happen. But, if you aren't careful, you stand to meet the behemoth that lurks at the Galactic Center.

Electra Wait. What's a behemoth?

Aethra In this case, it is a super-massive black hole, weighing in at well over a million solar masses, that lives in the central nuclear star cluster surrounding the very heart of our Galaxy.[4]

Electra A super-massive black hole (SMBH)?!? What's their story?

Aethra They are dark, and do not emit light. And they are very dense; typically smaller than a planet in diameter. You will only ever be aware of them from their gravitational influence. For example, if you drift within the central parsec[5] or so of the central nuclear star cluster, you will start to feel the gravitational influence of the central SMBH non-negligibly. That is, your trajectory will start to be dictated almost entirely by the gravity of the SMBH. The total masses of SMBHs in the Universe can range anywhere from 10^6 to 10^{10} times the mass of a typical star.[6] In our own Milky Way, the super-massive black hole is only about 4×10^6 times the mass of a typical star, so it's rather puny compared to some of the other SMBHs in the Universe!

Electra Okay, that sounds like a lot of power. A Destroyer of Worlds. A Deliverer of Death.

Aethra It is. If stars drift too close to the central behemoth, they can be torn apart. Their corpses are briefly crushed upon approaching very close to the SMBH, and they become extremely luminous for a brief time. Some of their corpse is eaten by the behemoth, and some escapes as high-velocity ejecta; the tenuous final remains of a once proud star. And, once inside an SMBH's belly, it is impossible to escape! The very laws of the Universe forbid it! [7]

Electra Oooookay. Gotcha. Stay the heck away from the SMBH lurking at the heart of the Galactic Center. I will keep my eyes peeled for it. Oh wait....it's invisible. Well, I guess I will just have to keep my wits about me.

Aethra I am glad, child, and wish you the best of luck. May the Cosmos bestow great luck upon you.

Electra That sounds pretty great, actually. I'll take two!

---

our Galaxy, then more than 100 stars will fall between the pair. The stellar densities are that much higher!

[4] GIVE SOME BACKGROUND ABOUT WHAT WE KNOW ABOUT SMBHS - THEIR TYPICAL MASSES, SIZES, HOW THEY FORM, OBSERVATIONAL PROOF OF THEIR EXISTENCE, ETC.

[5] MAKE SURE THE TERM PARSEC IS DEFINED UPON ITS EARLIEST APPEARANCE.

[6] Typically, we define astronomical masses this large to be in units of the mass of the Sun. However, since there is no a priori reason for Electra or Aethra to be aware of our Sun, and the Sun is remarkably representative of the average or typical star in our Galaxy, we will define units of mass with respect to a "typical" star or, equivalently, the Sun.

[7] DEFINE A TIDAL DISRUPTION EVENT AND PROVIDE SOME BACKGROUND.

4.2 Journey to the Heart of the Galaxy

Narrator Electra continued her inevitable journey toward the Galactic Center, now too far from Aethra to see or hear her. Along the way, Electra met a number of colorful characters. The first of these, Dardanus, took a particular interest in understanding her trajectory through the Galaxy. She came upon him while traveling through the low-density Galactic field, No Man's Land, slowly drifting by at a distance, but close enough that they could hear each other bellow from a distance.
Dardanus Hello there! My name is Dardanus. Where are you off to in such a hurry?!
Electra Hello! I am Electra. Well, if you take my current trajectory through the Galaxy and propagate it forward through time, it looks to me like I am ultimately heading for the Galactic Center.
Dardanus Great! Wait... What is a "Galactic Center"?
Electra As far as I know, it is the very Heart of our Galaxy. There, a dense nuclear star cluster lives, where the stellar densities are extremely high. If I have my math right, it is about a million times denser in nuclear star clusters than it is here!
Dardanus Wow! That sounds crowded. I bet you can hear *everything everyone* is doing or saying, at any given moment.
Narrator Dardanus shudders at the thought of living in an environment devoid of privacy, having grown used to the relative isolation characteristic of No Man's Land; it has been home to him for many billions of years now.
Electra But the really terrifying thing, if you ask me, is the super-massive black hole lurking in the central nuclear star cluster.
Dardanus A super-massive black hole, you say? What is that?
Electra It is a dense dark object that does not emit light. If I remember right, they have total masses that can range anywhere from 10^6 to 10^{10} times the mass of a star such as yourself. In our own Milky Way, the super-massive black hole is something like 10^6 times the mass of a typical star. So it's massive, but not compared to the rest of its siblings.
Dardanus Holy cow! That's a lot of mass. In fact, couldn't things potentially get violent if you were to wander too close to an SMBH?
Electra Uh... Yeah, it's very possible. Technically, if you wander too close to a super-massive black hole, it can eat you whole. And, once inside its belly, you can never escape.
Dardanus Oh, wonderful! That doesn't sound even remotely terrifying...
Electra That's what I've been saying!
Narrator Dardanus was no stranger to sarcasm.
Electra Um... And even if you don't get eaten, if you *do* wander close to a super-massive black hole, you are almost certainly going to get accelerated to extremely high velocities. Like, we are talking thousands of kilometers per second.
Dardanus WHAT?! Is that even possible?

Electra Yep, such fast stars have definitely been seen whipping through our very own Galaxy, presumably on their way out. I know, I've seen a couple since leaving my birth cluster.
Dardanus Well, I said it once and I'll say it again: this all sounds very terrifying. You're definitely going to need to keep your wits about you in there.
Electra Exactly! I mean, given all these hurdles, how can I possibly expect to adequately prepare myself for a journey through the central nuclear star cluster of the Milky Way? What I'm trying to say is: I'm definitely going to die in there!
Narrator Dardanus yawns, tired from a rare conversation.
Electra Do you even hear me? *I am going to die for sure!* And there's nothing I can even do about it.
Dardanus Well, if I were you, the first thing I would do is take another nap, frankly. I figure you'll need to be fresh and alert for the end of the long journey to get yourself to the Heart of the Galaxy.
Electra SLEEP?!? Who has time for sleep? I need to craft an ingenious survival plan, gather supplies, panic a few more times, etc. You get the idea.

Dardanus had already fallen asleep, now snoring loudly.
Narrator Long after parting ways with Dardanus, Electra too falls asleep...although the frequent and violent nervous twitching appears anything but peaceful.

4.3 Befriending the Beast

Narrator Electra awoke surrounded by stars. This definitely was not the Galactic field anymore. Recalling her trajectory through No Man's Land before falling asleep, Electra suddenly realized where she was.
Electra The Galactic Center! I made it! Hello there! Can you tell me: Is this the nuclear star cluster at the heart of the Milky Way?
Narrator A nearby star named Carystus turned to face Electra, the confusion evident on his old face.
Carystus Well, to be honest, I've lived here my entire life, and I really have no idea what stars in the rest of the Galaxy call this place. But, what I can tell you about this unique place in the Galaxy, is that you will not find a more extreme population density anywhere else in the entire Milky Way. We pride ourselves on our crazy stellar densities, reaching as high as $\sim 10^7$ stars per cubic parsec!
Electra , Yep, this *must* be the Galactic Center I have been looking for. The behemoth must be close!
Carystus Behemoth?
Electra Allegedly, a super-massive black hole resides here somewhere, hiding among its many luminous denizens.
Carystus Oh! You must mean Chiron. He's here alright. Knowing when you are close is one thing, but finding him without being eaten is altogether another.
Electra Oh wow! He sounds dangerous but illusive. Just like he was described to me! Any tips for how best to approach him? I'd very much like to meet and interact with him... I mean, from a safe distance.

Carystus You are a brave one! That is a good question. Hmmmmm... Well, Chiron is surrounded by a dense population of massive stars, directly orbiting his significant center of mass.[8] These stars all emit winds from their surfaces, at a rate of many thousands of times the mass of a typical star per year.[9] This is fast enough that, within almost no time, Chiron will collect their expelled gas in to a compact disk, which he accretes from and is thus his main source of fuel. This disk, once formed, should emit light and be luminous; it is directly visible to us all on its own, even if Chiron is not. But, without a doubt, Chiron will reside at the center of any such disk, called an "accretion disk". This is where you can be sure to find him.
Electra Look for a small but bright accretion disk at the very center of this nuclear cluster. This will clearly and unambiguously identify Chiron . Gotcha!
Carystus Yep, that's about it. If you can do that, you'll behold the beast.
Electra That's the goal!
Carystus Just be careful. Super-massive black holes have a mind of their own, and can be unpredictable. Strange physics you might not be used to can emerge and even dominate the picture in this new high-gravity regime.[10] When these effects become important can be hard to identify before they are right on top of you. So one must take great care to safely navigate such an extreme and dangerous environment.
Electra I read you, loud and clear. I definitely intend to keep my wits about me. Well, I'm off to meet Chiron. Wish me luck!
Carystus Good luck, my child. May the brightest of futures befall you.

[8] DESCRIBE WHAT IS KNOWN FROM OBSERVATIONS ABOUT THE INNER 0.1 PC OF THE MW.

[9] Describe mass loss in massive stars and describe their basic evolution compared to low-mass stars.

[10] BRIEF INTRO TO GENERAL RELATIVITY!

Chapter 5

A Bond Forged of Fire

Narrator After the dissolution of their natal star cluster, Maia and Merope wandered through the Galactic Disk. Millenia passed without much in the way of interruption; Maia had only Merope to keep her company, and vice versa. Now and again, the sisters encountered a passing star off in the distance, too far away to exchange a conversation. Regardless, they yelled relentlessly, eager to meet a new face. After a few million years of this, the pair had grown bored, but inseparable.

5.1 An Old Star...

Narrator Merope 's age was now showing. The most massive of her siblings, she was destined to burn through her nuclear fuel the fastest.[1] She was now reaching the end of her short life. As such, she had begun to expand, slowly entering the red giant phase of stellar evolution.[2]
Maia Uh... I don't mean to alarm you, Merope, but I've noticed you've been expanding lately. I mean, just a little bit. No big deal, really. But, uh, where do you suppose this is heading?
Merope Uh... Well, I hadn't noticed, to be honest. But now that you mention it, I do feel a little bloated.
Maia Well, you look *great*, that's for sure.
Merope Thank you, sister. But I fear this is going to get worse before it gets better. Much much worse, in fact. I seem to be expanding further...
Maia Oh dear. Well, don't panic. We'll figure this out. How do you feel?
Merope I feel... Cold. Do I look cold to you?
Narrator Merope was shivering noticeably.

[1]To remind the reader, the most massive stars have the shortest lifetimes since, in spite of having more nuclear fuel, they are able to burn through their entire energy reservoirs faster.

[2]Recall that during the red giant branch phase of stellar evolution, stars can expand up to several hundred times their size on the main-sequence. When the Sun eventually reaches the red giant branch phase, several billion years from now, it is likely to expand out beyond the orbit of Earth, engulfing the planet.

Maia Eeesh... Yeah, kind of. You've been getting steadily redder in color. It's not drastic, but it is noticeable.[3]
Merope Um... Okay, maybe if I hold my breath *that* will stop the expansion. Worth a try, I suppose. Here I go...
Narrator Merope drew in a deep breath, and held it. The minutes passed. Her face blue, Merope eventually exhaled in defeat.
Merope Oh no. That was uncomfortable. And I am still expanding.
Maia Don't panic. We'll sort this out.
Merope You already said that!
Maia Well, frankly, I can't emphasize it enough. Just... Don't panic.
Merope You aren't making me feel any better over here.
Maia I'm sorry. I'm doing my best... I know I said not to panic, but I'm losing it over here myself...
Narrator Maia was noticeably agitated, pacing back and forth.[4]
Maia Yep, I'm dropping the ball. Big time.
Merope Jeez, Maia, get ahold of yourself. I'm the one who seems to be expanding to certain doom, and yet you are the one hyperventilating.
Narrator Maia was rapidly fluctuating in brightness, caused by the hyperventilation.
Narrator Flabbergasted, Maia struggled to regain her composure.
Maia It's fine. I'm fine. How are you doing?
Merope Well, quite honestly, I continue to expand. How do I stop?
Maia Have you tried thinking really hard about *contracting*?
Merope Really? I'm about to die, and your big idea is to think good thoughts?
Maia Well, it can't hurt...
Merope You aren't helping!
Narrator By this time, Merope had already expanded by over an order of magnitude, and her radius was still growing rapidly.
Maia I'll go get help!
Merope And how are you going to do that? We're gravitationally bound.
Maia Oh right. Gravity. Okay, new plan: I'll think good thoughts?
Narrator Merope sighs in defeat.
Merope I'm going to die for sure.
Maia Don't say that, Merope You're not going to die.
Narrator Eventually, Merope stopped expanding and stabilized.

[3] As stars expand on the giant branch, their effective or surface temperatures decreases. The reason for this stems from a formal relationship between the radius, luminosity and surface temperature of a star, called the Stefan-Boltzmann law. The general trend of larger radii corresponding to cooler surface temperatures, at a given mass and evolutionary stage, is consistent with the basic idea that larger radii correspond to surfaces with a larger displacement from the core, which is where energy is generated in stars. Hence, the total energy diffusing through the stellar surface per unit time (i.e., the total luminosity) is smaller, and so is the effective temperature. CHECK

[4] This pacing occurs in the radial direction, and can ultimately be characterized by the orbital eccentricity: more eccentric orbits have larger (fractional) radial amplitudes, at a given orbital separation. In other words, more eccentric binaries are more agitated. PICK OF ORBITAL DYNAMICS AND MORE THOROUGH DEFINITION OF ORBITAL ELEMENTS AND ECCENTRICITY?

Maia Whoa! I think you've stopped expanding!
Merope Oh thank the Heavens! I do indeed seem to have stopped. Phew! What a relief!
Maia Well, look at you! You've definitely stopped expanding. You're much much redder and, well, larger than you used to be...but none of that is changing anymore. I think you're going to be okay!
Narrator Merope breathed a long sigh of relief. The life of a massive star was anything but easy, but Merope remained optimistic that the aging process would grow easier as time went on.

5.2 Blown Out of Proportion

Narrator For some time, it seemed Maia had proved right. But eventually Merope began expanding again. Over the next few million years, she eventually grew accustomed to it. Just another day in the life of a massive star.
Narrator But then, one day, suddenly and without warning, Merope exploded. A supernova! Plasma and gore flew passed Maia , spraying her face with the guts of Merope and knocking her backward. The blast was asymmetric, escaping mostly from a preferred side which happened to oppose Merope 's orbital motion almost perfectly. Due to angular momentum conservation, this meant a significant and almost instantaneous reduction in Merope 's orbital velocity and a loss of orbital angular momentum.[5] Merope drifted inward, closer to Maia and on a much more eccentric orbit than before.[6]
Maia Merope! Are you alright?!
Merope Uh... I think so. Give me a minute here. I feel much lighter.
Maia Well you did just eject your outer envelope and most of your mass in a rather dramatic supernova explosion. So it makes sense that you are much less massive now. You look so small and compact!
Merope Thank you! I feel pretty svelte over here. Looking good, feeling good. Who would have thought exploding could be such a positive experience?
Narrator A worried expression appeared suddenly on Merope 's face.
Maia What's wrong?
Merope Does your belly always do that?
Narrator Maia looked down to discover her midsection had grown distended. A bulge pointed directly toward Merope .[7] As Merope re-approached the

[5]EXPLAIN THIS USING CONSERVATION OF MOMENTUM, AS WELL AS CONSERVATION OF BOTH ENERGY AND ANGULAR MOMENTUM.

[6]EXPLAIN THE CONCEPT OF ORBITAL PARAMETERS, AND PROVIDE THE DEFINITION OF ECCENTRICITY BY DISCUSSING ELLIPSES.

[7]Gravity exerts a differential force across the extent of finite-sized objects. In practice, for example, consider the Earth-Moon system. The gravitational force exerted by the Moon on the Earth is strongest on the side facing the Moon, and weakest on the opposing side, since the force of gravity falls off as the inverse of distance squared. This causes the side facing the Moon to become extended, or to "bulge out" toward the Moon. Called a "tidal bulge", this is the mechanism responsible for tides in the Earth's oceans. PROVIDE AN ILLUSTRATION FOR CLARITY.

point along the orbit corresponding to closest approach with Merope,[8] the bulge grew and a thin stream of material began to flow from Maia 's surface toward Merope .[9]

Maia Holy cow! Now I'm losing mass! Okay, don't panic.

Merope I swear, if you say that one more time I'm going to scream.

[8]Orbits can be either circular or elliptic. In the former case, both objects maintain a constant distance from their mutual center of mass. In the latter, or "eccentric", case, the distance of each object changes with respect to their mutual center of mass. The point along the orbit corresponding to the distance of closest approach between the objects is called "pericenter" or "periastron", whereas the opposing side (corresponding to the point of furthest approach) is called "apocenter" or "apoastron".

[9]Consider a line connecting the centers of mass of two objects in orbit about each other. Somewhere along this line, the force of gravity exerted by each object is exactly balanced (the location of this point depends only on the masses of the two objects). If the radius of one star expands beyond this point, then the matter on the outer surface of the star is more strongly attracted gravitationally by its binary companion. In such a scenario, the mass flows from the surface of the large star onto the surface of the other, flowing through the point where their mutual gravitational force is precisely balanced. Mass transfer ensues. This critical surface is called the "Roche lobe".

Chapter 6

A Tale of Two Black Holes...

Narrator Sterope was trapped in an ancient globular cluster and in search of a pair of black holes. The idea was to first encounter a binary star system, undergo a chaotic three-body interaction, and ultimately become exchanged into it. From there, she need to find a black hole, undergo another a chaotic three-body interaction, and eject her former binary companion. Finally, she needed to encounter a second black hole and undergo yet another chaotic three-body interaction, this time with two black holes. In the end, she hopes to be the one ejected, leaving the two black holes behind in a binary and escaping from the cluster altogether.[1]

Narrator She wandered through her new and hopefully temporary home for many millions of years. During this time, she endured many encounters with the other denizens of the cluster. But it took several such interactions before she eventually met even one black hole. Finally, she stumbled upon a suitable target. Sterope had managed to exchange herself in to a normal stellar binary by the time she encountered the first black hole. As the black hole drew close, its gravity pulled Sterope and her companion toward it. A chaotic three-body interaction ensued. A delicate dance, the three bodies bobbed and weaved by each other, continually accelerated by each other's mutual gravitational attraction. They took turns being flung out far from the system center of mass, on loosely bound excursions. All this, but without imparting enough kinetic energy for any one of them to escape, each excursion carefully choreographed such that they remained bound, destined to return to rejoin the melee. The dance continued until, eventually, Sterope's original companion was ejected, flung off at sufficiently high velocity to escape to what amounts to spatial infinity in Sterope's reference frame.[2]

[1] DESCRIBE THIS PROCESS IN DETAIL, AND DICUSS ITS RELEVANCE FOR CHAOS. PERHAPS SHOW THE HUT & BAHCALL FIGURE OF THIS?

[2] DISCUSS THE CONCEPT OF SPATIAL INFINITY, AND REFERENCE FRAMES.

6.1 A New Companion...

Sterope Uh... Hello there... Wherever you are. I can't actually see you, you being completely black and all. But I know you're there! I must be orbiting *something*, after all.
Ares You are not alone. It is I, Ares. Star destroyer. Devourer of worlds.
Sterope That sounds scary. Regardless, I'm pleased to meet you. I've been searching for a black hole such as yourself for quite some time.
Narrator Sterope extends an eager hand, hoping for a handshake but suddenly realizing Ares could easily be out of reach.[3]
Ares You aren't scared?
Sterope Scared of what?
Ares Me! I just said I destroy stars!
Sterope Oh. Right. Well I wish you the best of luck with that, but so far you seem nice enough.
Narrator Ares lets out a long sigh.
Ares All this mass, and nobody around here seems to care. What gives?
Sterope I don't know, but *I* sure care. That's why I came looking for you. I need an object of significant mass to help me escape from this cluster. Well, two massive objects, to be precise.
Ares Ah, you are in need of a gravitational assist! A slingshot from a massive body. Finally, a use for me![4]
Sterope Yes! You could be very useful to me.
Ares Wonderful. I feel useful already.
Sterope Okay, so, how do we do this?
Ares Well, I guess I could take a run toward you, and maybe that would work?
Sterope I don't think so. We are gravitationally bound. I do believe we need at least some form of outside interference to unbind us. After all, the excess energy must come from somewhere.[5]
Ares Fair enough. We need another black hole!
Sterope Exactly! I am confident that, between the two of us, we can find one.
Ares I might know where. My brother is lurking around here somewhere.
Sterope You're brother?!
Ares Zeus ! Zeus ! Where are you, brother?
Narrator A long silence passed. Sterope , excited at the prospect of a second black hole, listened closely for a response. Finally, a response came.
Zeus I am here.
Ares Wonderful. Good to hear your voice again, brother.
Zeus And you, brother.
Ares I have met a friend, Sterope , who requires our assistance.
Zeus Hello, Sterope . Nice to meet you.
Sterope And you, Zeus . Truly, this is intimidating. You are both *so* massive.

[3] AGAIN, DO WE WANT THE STARS TO HAVE HANDS?
[4] DEFINE THE TERM GRAVITATIONAL ASSIST.
[5] REMIND THE READER ABOUT ENERGY CONSERVATION AND ORBITAL BINDING ENERGY.

Zeus Do not be intimidated, child. Our mass can at best accelerate you, nothing more.
Sterope You are both so kind. I don't understand why everyone I met before you was so afraid of black holes.
Zeus A common misconception.
Ares Sterope is in need of a gravity assist, to escape from this cluster.
Zeus I see. Well, you seem kind, noble and out of place here amongst these old stars. I am happy to offer my mass in the name of this cause. But how do you propose we get the job done?
Ares As god of war, I have facilitated many a squirmish in this cluster environment.[6] As I see it, there is no better way to impart a velocity kick of sufficient magnitude to eject Sterope from the cluster. Us three must engage in a chaotic dance, choreographed by none other than gravity.
Zeus Very well. I am coming toward you. Prepare yourselves for chaos!
Narrator Zeus drifted ever closer to Sterope and Ares , slowly at first but rapidly gaining speed. Before they knew it, Zeus was upon them, tugging them in every which direction, and vice versa. Chaos ensued. The two black holes and Merope completed a series of wild loops and orbits.[7] More than a few times, Merope passed close enough to one of the black holes to really feel their gravitational might. The differential force of gravity caused matter to be pulled from her surface after making her closest approach.[8] Not much matter, but enough to freak out both her and her interloping black hole; each time this occurred, they exchanged a startled glance. Finally, Merope was ejected at high velocity, leaving Ares and Zeus bound in a new binary.
Ares I think that should do it.
Zeus Agreed! Surely she must be flying away at above the escape velocity.
Ares Fare thee well, Sterope ! May only glorious adventures befall you!
Sterope Thanks so much, to the both you! Free at last!
Narrator Sure enough, Sterope escaped from the gravitational bounds of her temporary host cluster with kinetic energy to spare. Her trajectory now pointed inward, back toward the Galactic Disk. Optimistic she would find her lost siblings, Sterope smiled at the thought of seeing them again..

[6] USE NσV ARGUMENTS TO EXPLAIN THE RATE OF SUCH INTERACTIONS.
[7] A SKETCH OR DIAGRAM DEPICTING THIS WOULD BE COOL AND USEFUL. AARON?
[8] Consider a normal stellar binary star system, composed of two stars. Recall that, due to tidal forces, the side of a finite-sized object closest to its binary companion will be more strongly attracted by gravity than the opposing side, raising a "tidal bulge". If the radius of one star exceeds the "Roche limit", then mass is transferred from the surface of the star onto the surface of its binary companion. The physics here is ultimately the same, but the dance is chaotic; this scenario occurs sporadically and pairwise over the course of the chaotic three-body interaction.

Chapter 7

The Beast Awakens...

Narrator Electra continued to wander closer to the very center of the Milky Way's nuclear star cluster. The stars in her immediate vicinity seemed to fly by faster and faster as she drew ever closer to her destination. Such high relative velocities could *only* be imparted via the gravitational acceleration supplied by some very nearby compact massive object, a description that fits Chiron to a "T".
Narrator Random perturbations from passing stars continuously deflected her orbit, causing her to wander throughout the nuclear star cluster somewhat aimlessly for what seemed like a very longtime. All the while, she searched for some sign of Chiron. Until one day, she saw the tell-tale signs of a thin, fleeting accretion disk. A soft halo of light surrounded a black sphere. Enrico had proved right: the super-massive black hole was indeed uniquely identified by the thin accretion disk Enrico had described to her, formed of the coalesced winds of nearby massive stars.[1]

7.1 The Behemoth of Black Holes

Electra Hello there! If I squint, I see what looks like an accretion disk hiding over there. Is that you Chiron?

par **Narrator** A long silence followed Electra 's seemingly innocent question. Eventually, the silence was broken. A deep booming voice responded, shaking Electra to her core.

[1] When matters falls deep into the local gravitational potential of a massive compact object, it often gathers into an "accretion disk". This is because the infalling matter carries finite angular momentum, which must be conserved. Hence, close to the black hole, the gas particles will sort themselves into an approximately planar configuration with the orbital plane being aligned with the total angular momentum vector. This planar configuration of gas particles is called an "accretion disk", since viscosity within the disk can cause angular momentum to be redistributed and dissipated. Hence, the inner material of the disk can lose enough angular momentum this way to eventually be accreted directly onto the compact object. The gas particles in the disk collide with each other, emitting light in the process and making accretion disks visible to observers on Earth.

Chiron Yes. It is I, Chiron. I am here, and you are there. But who is it that I am speaking to?
Electra I am Electra . A wandering star in search of my lost sisters.
Chiron I see. You have spotted what remains of the corpse of my last meal. The scene before you might look a little gruesome but, I assure you, it is but one aspect of all that must be. I do my part, here in this most extreme of environments in our Galaxy. The stellar density can only grow so high, after all. Otherwise, we'd all be banging into each other on a nearly daily basis.[2]
Electra Of course you do! I did not mean to accuse you of anything. I cannot thank you enough for all that you do. I am here in the hopes of meeting you, to draw upon your incredible wisdom and learn about my place in the grand scheme of things. I was born of a particularly compelling Giant Molecular Cloud, and have been wandering my way through the Galaxy ever since, independent of my siblings. As did I, they ventured off in random directions when my Mother dispersed.
Chiron I see. A quest! But with what purpose?
Electra That is the question! I suppose I am here to understand. To fully digest this Universe we call home, while avoiding falling victim to it. Experience its many wonders and breath-taking panaromas! Eventually, I hope to reunite with my sisters, and hear their lovely voices one more time.
Chiron . A good answer, young one. You have come to the right place, if gaining perspective is your goal. This part of the Galaxy is unlike any other. Extreme stellar densities, recent and even ongoing star formation, collisions and high-velocity impacts mediated by a super-massive black hole (i.e., me), etc.[3] Being here and witnessing these types of events will surely help you to better understand them, gaining further insight to the inner machinery of the Universe.
Narrator Wide-eyed and eager for answers, Electra was all in.
Electra I am intrigued! How *do* they work?
Chiron Come a little closer, child. I can barely hear you.
Electra Oh sure, of course. That makes sense.
Narrator Electra deflected her orbit to bring her a little closer to Chiron.
Chiron The first thing I shall teach you is that, the closer you are to a massive object and, more generally, the more mass you have very close to you, the

[2]Recall that the stellar densities can reach up $> 10^7$ $M_\odot$ pc^{-3} in the Milky Way's central nuclear cluster. At such high densities, the rate of direct collisions between single and binary stars, and even between two single stars, can be very high. There is also the issue of stars diffusing into the "loss cone" of the central SMBH, which refers to the family of orbits that drift sufficiently close to the SMBH that the orbiting star will be eaten by the SMBH, usually in the form of a tidal disruption event (see below). This also serves to deplete stars from the local stellar population, reducing the stellar density. The diffusion rate of stars into the SMBH loss cone be very high when the density is high, but drops off significantly at low densities.

[3]If a star travels very close to an SMBH, a significant gravitational acceleration can be imparted. in fact, if another star or BH is involved (required for conservation of energy and angular momentum), then a "hypervelocity star" (HVS) can be produced, escaping with a final velocity up to many thousands of kilometers per second (provided it avoids a tidal disruption event; see above). Such HVSs have actually been observed in our Galaxy, with a few candidates seeming to have originated from the Galactic Center, as expected if the HVSs formed from an interaction with the central SMBH.

acceleration imparted to you per unit time will be greater. In other words, you will notice that your velocity relative to your accelerator and even other nearby stars, increases.

Electra Yes! I have noticed that! Just now, I came closer to you, and I am now orbiting you at higher velocity. Is that the effect you speak of?

Chiron Yes, that is exactly it. Very good. But I can still hardly hear you. Come a little closer still; be kind to these old ears.

Narrator Electra drew ever closer to Chiron, her typical orbital velocity now several hundreds of kilometers per second, and her mean orbital distance no more than a fraction of a parsec. Her orbit about Chiron had grown increasingly eccentric and, at pericenter, she was about a thousand times her own radius from Chiron's center of mass.[4]

Chiron That is good. I can now resolve your face with these old eyes, at least. Wonderful to meet you, my child.

Electra And you, Chiron! What else can you tell me about the Universe?

Chiron Well, you have probably noticed that more massive objects exert a greater gravitational acceleration, at a given distance from their center of mass.

Electra Oh yes. That was one of the first things that I noticed. When my Mother dispersed, and her considerable mass along with it, my siblings and I became gravitationally unbound. I have not seen them since, but the memory is still with me as if it only just happened yesterday. I do miss them.

Chiron I can only imagine, child. Perhaps I can help you to find them.

Electra That would be wonderful! Do you know where they are?

Chiron I think that I might. Come a little closer still, child, this is a secret best kept between friends. We will need to whisper in each other's ears in such a crowded environment.

Narrator Electra did as requested, bringing her pericenter distance even closer to Chiron. But she could now feel the consequences of her decision; at apocenter, her velocity was very low relative to other stars in her vicinity. This meant that she could feel the individual gravitational perturbations from passing stars; each one seemed to knock her on to an even more eccentric orbit relative to Chiron. If this continued, she would only drift closer to him. It seemed there was now no going back.[5]

Narrator Electra realized she had mistaken a gaping maw for a warm smile. Now that she could actually see Chiron's face, she recognized the hunger. And she suddenly realized she had been selected as the next meal. But her fate was now sealed. Without outside help, there was nothing she could do to avoid ever higher eccentricities, and hence ever smaller distances of closest approach.

---

[4]Note that this lies well outside the tidal disruption radius. Another order-of-magnitude reduction in the distance at closest approach, however, and TDEs should become increasingly common.

[5]DESCRIBE HOW SUCH PERTURBATIONS INCREASE ECCENTRICITY, USING CONSERVATION OF ENERGY AND ANGULAR MOMENTUM.

7.2 A Change of Heart in the Heart of the Milky Way

Narrator And, sure enough, a few orbits later, Electra came within about a 100 times her radius from Chiron's center of mass. A differential force like she had never felt before was exerted upon her. She was stretched (along the direction of her orbital motion) and squeezed (perpendicular to her orbital motion) as she completed each orbit, and it was only getting worse as time passed. In spite of this discomfort, Electra remained blissfully unaware of Chiron's true intentions.
Electra I do like you, Chiron. You are being so kind to me. You offer answers, and yet I have nothing to offer you in return. Is there anything I can do? A hug, at the very least, perhaps?
Narrator Electra tried to extend herself in Chiron's direction, hoping to bestow upon him a firm embrace like he had never known before. Chiron could see the sincerity etched across Electra's face, scrunched up in concentration as she tried to deliver the hug she felt strongly Chiron surely must need. Touched by this, Chiron suddenly began to cry. Deep, woeful sobs racked his torso.
Electra Oh my goodness! You are in pain! What is wrong? Have I done something wrong?
Chiron No, child. It is quite the opposite. You have reminded me of the purity and sincerity you young, hopeful stars often possess. Ah, how I have missed that. It has been a long time, you must understand.
Electra Oh, I think I can understand. I mean....I'm happy to try, at least.
Narrator sadness appeared suddenly on Chiron's face.
Electra What is wrong, Chiron? Please allow me to help.
Chiron I fear there is something about me you *cannot* understand.
Electra Well, try me! You'll have to give it a go to find out for sure.
Narrator Chiron sighed.
Chiron Very well. I was once like you. A young star, wandering the Universe. Completely free and excited for the adventures I was sure would befall me. And, indeed, I saw many an adventure. But, like all things, I eventually reached the end of my long life. I was a massive star, once upon a time, and when my nuclear fuel ran out I became a black hole. Back then, I wasn't much more massive than you are now, even as a black hole. But, because of our considerable mass, we black holes are cursed to encounter other objects on much shorter timescales than other stars, especially in dense environments.[6] And, when we do, there is a good chance we will consume them, devouring them whole. Each time, we become a little more massive, slowly growing.
Chiron In my case, I found myself in a very dense environment when I first became a black hole. Stars whipped by me all the time. Before I knew it, they

[6] Recall that the rate of direct collisions is proportional to the collisional cross-section, which defines an area that, if both stars pass through it at the same time, their radii would overlap directly and a collision would occur. Provided objects have sufficiently slow relative velocities, "gravitational focusing" (i.e., gravity curves the relative trajectories of the passing objects and focuses them more toward each other) can significantly increase the collisional cross-section and enhance the collision rate.

were drifting too close to me, and my gravitational pull ripped them from this world. They call it a *tidal disruption event.*[7] At closest approach to the black hole, the culprit star is stretched along the direction of its orbit, and squeezed in the direction perpendicular to it. The star's brightens grows immensely due to this compression, at least briefly, but most of its mass falls back and is ultimately eaten by the black hole.
Electra So you ate a lot of stars?
Chiron Yes. It was accidental at first, but eventually I became fixated on the idea of becoming even more massive. I became mad, and left my *stellarity*[8] behind. I do not want to be this devouring black hole anymore. I wish to help and connect with my fellow stars and remnants.
Electra Well, I forgive you, Chiron. And I appreciate your honesty.
Narrator Once again, Electra struggled, unsuccessfully, to hug to Chiron.
Chiron Thank you, child. I am truly glad to have met one such as you, a kind soul out here in the harshest of environments.
Electra Aw, shucks. Happy to help. And I'm glad to have met you too!
Chiron To be honest child, I was begging you ever closer earlier in an attempt to consume you. But I no longer have the stomach for it. I am far too fond of you now.
Electra And I you, Chiron. I was wondering why I kind of feel like the progenitor of one of those tidal disruption events you mentioned every time I reach pericenter...
Chiron It is still good news! From your current location, I can impart a significant acceleration to you. This would easily give a sufficiently high velocity for you to escape from here, and hopefully find your lost siblings.
Electra That would be great! What do we need to do?
Chiron Well, we will need another moderately massive star or remnant. More massive than you, certainly. This will be needed to maximize the probability that it is you who is ejected.[9]
Electra Wait, what? I might *not* be the one ejected? So this is *not* a guarantee? Uh.. Okay, let's say I am not ejected. What do you suppose would happen instead?
Chiron Uh... Well, most likely, I would consume you as a tidal disruption event.
Electra WHAT?! Are you crazy?
Chiron Well, you have a very large physical size compared to a black hole. It *significantly* increases the probability of you colliding with another object

[7] Recall that this is when a star passes too close to an SMBH, and is torn apart by the induced tidal forces, often triggering a very bright flare.

[8] Stellarity is to stars what humanity is to humans.

[9] During a chaotic gravitational interaction involving three or more particles, the least massive particle is almost always the first to be ejected. The reason is simple: the imparted force is large and so is the resulting acceleration due, respectively, to the larger masses of the other particles and the lower mass of the ejected particle. The probability of ejection for the lowest mass particle quickly asymptotes to unity as the mass ratio goes above about 10 or so; for very low-mass particles, they are almost guaranteed to be ejected (if they are not first destroyed during a TDE event or collision).

directly in *any* scenario.[10] Do not worry though. It is all about choosing the right third object for the job.
Electra Okay. What should the third object be?
Chiron Preferably another massive black hole. We have small physical sizes, but large masses that can impart significant accelerations at larger distances.
Electra Okay, great. Let's find another massive black hole!

7.3 The Gravitational Slingshot

Electra Wait.... How exactly *do* we find another black hole?
Narrator Chiron whistled suddenly, clearly trying to get someone's attention.
Chiron Hippe, my daughter, are you there?
Narrator Only a moment had passed when the response came, loud and closer than Electra had anticipated.
Hippe I am here, father. What is it that you need?
Chiron You assume I do not seek you simply to talk? To ask you how you are doing?
Hippe Well? Is that why you have sought me out?
Chiron Uh... Yes! How are you, my child!?
Hippe I am well, father. As you know, this is the one place in the Galaxy that food is plentiful.
Narrator Chironglances awkwardly at Electra. An anxious laugh escapes from Chiron's lips.
Chiron Ha ha, yes, well I have put myself on a very strict diet lately. I am, after all, the fattest black hole in the Galaxy, with the next fattest black hole lying as far as several hundred megaparsecs away. No need to exacerbate the problem, your mother used to always say.
Hippe Uh... Sure, Dad. Whatever you say. So why did you *really* call me?
Chiron To say hello, of course. But, now that you mention it, I could use a small favor.
Narrator Hippe sighed.
Hippe What is it that you need, father?
Chiron I am in need of a gravity assist for our friend Electra here. She needs to be imparted with a sufficiently high velocity kick that she may venture off throughout the Galaxy in search of her siblings.
Hippe I see, the ol' gravitational slingshot. That shouldn't be a problem. Believe it or not, we black holes are often called upon for a gravity assist. The

[10] Recall that a tidal disruption event (TDE) is what occurs when a star passes too close to a massive black hole. Close to the BH, gravity is sufficiently strong to deform the star (stretching it along the orbit and squeezing it in the radial direction, perpendicular to the (instantaneous) orbital trajectory). The star can be squeezed sufficiently to brighten it by many orders of magnitude, often resembling a supernova explosion. The event is so violent, that the star is usually ripped apart, with some of thee debris remaining unbound and escaping from the immediate vicinity of the BH, and the rest either being accreted directly onto the BH or sorting itself out into an accretion disk around the BH.

curse of being massive! Well, you can certainly count me in. It is wonderful to meet you, Electra!

Electra And I you, Hippe. I can't thank you and your father enough for your gracious offer to assist me. To escape this nuclear star cluster and its deep potential well, I am truly at the mercy of your considerable mass. I am truly grateful for any acceleration you can bestow upon me.

Hippe It will be a pleasure, child. Okay, let's get this show on the road. Let me just get a running start at you...

Electra Uh... A running start...?

Hippe Yeah, yeah, don't sweat it. I need to smash in to the both of you at sufficiently high velocity to kick you out and get you where you need to go.

Electra Whoa, whoa, whoa! Maybe we should talk about...

Narrator But it was too late. Hippe had already gotten her start, and was careening toward Electra's and Chiron's mutual center of mass (but skewed toward Hippe, the less massive of the two black holes) with startling precision. Hippe kept her relative velocity low, only a few kilometers per second relative to Chiron and Electra's mutual center of mass. Electra screamed in terror as her savior came toward them, the binary's mass pulling Hippe in and accelerating her toward the pair more noticeably at the last minute.[11]

Narrator A rather violent and chaotic dance ensued between Electra and the two massive black holes. When only two bodies are gravitationally bound, Kepler's Laws dictate the time evolution of the system.[12] But when a third body is randomly thrown in to the mix, chaos ensues. All Hell breaks loose. Each star undergoes a strong gravitational interaction with one or both of the other stars in the system, and recedes on some orbit defined by the exchange of energy and angular momentum during said close interaction. After completing this temporary orbit, the star returns toward the center of mass of the system. Upon getting there, each body is perturbed again, and leaves on a new temporary orbit. This process continues until, eventually, one of the particles is imparted with sufficient kinetic energy that it escapes to spatial infinity.[13] Due to energy equipartition and conservation of momentum, it is typically the lowest mass star that is ejected, and it usually leaves at the highest possible velocities.

Narrator The particular three-body interaction currently under our scrutiny proves to be no exception. Chiron, by far the most massive of the trio by several orders of magnitude, hardly felt the gravitational influence of either Electra or Hippe. He moved about little, his velocity relative to the system center of mass

[11] Recall that, by Liouville's Theorem, the total volume in phase space for a self-gravitating system of particles is conserved. In practice, what this means is that interactions with a more negative total energy are more likely to accelerate particles to larger velocities over the course of the interaction. By keeping her velocity low relative to the binary system center of mass, Hippe minimized the (positive) kinetic energy she brought in, thereby minimizing the total encounter energy (i.e., by making it more negative, due to the contribution to the total energy from the binary orbital energy).

[12] In a nutshell, thanks to Kepler, we can easily calculate everything we would ever want to know for the two-body problem.

[13] This assumes point particles, whereas if finite particle sizes are considered collisions must also be considered

never exceeding a few kilometers per second. His daughter, however, was much less massive than him, and his gravitational influence pushed and pulled her in every which direction. Electra, by far the least massive of the trio, felt the brunt of it. She was accelerated more than the other two, orders of magnitude more relative to at least Chiron. Eventually, she escaped at about 1,100 kilometers per second. But, by some miracle, she was left completely unscathed.

Electra Thank you so much, Chiron and Hippe! I cannot thank you enough. I will remember you always, and keep your memory close in my heart.

Narrator Both Chiron and Hippe smiled.

Hippe I see why you liked this one, father.

Chiron She is indeed special. Innocent and sincere in the most wonderful of ways.

Narrator Hippe shouted one last goodbye to her new friend:

Hippe Goodbye and good luck, Electra. My father was right about you! You have a warm heart! I wish you all the luck in the Universe!

Narrator Chiron was quick to join suit in extending his best wishes, and goodbyes.

Chiron As do I, child. Stay true to your heart, and you will be just fine. May the Cosmos protect you always, and carry you wherever you need to go.

Narrator Quickly receding in to the distance, Electra shouted one final goodbye:

Electra Farewell, to the both of you! I cannot thank you enough for your help. I will carry you with me always, and hope you will do the same. And I will of course tell my siblings all about you, when I find them!

Narrator Electra had now drifted far enough away from the central nuclear star cluster in the Milky Way that she was no longer visible to her new friends; if she could no longer see them, they certainly couldn't see her. Alone, she was not discouraged. After all, she was on her way, in search of her lost siblings. Hopeful that she would soon find them, Electra dozed off, falling fast sleep for the next several million years.

Chapter 8

The Making of a Millisecond Pulsar...

Narrator Merope was now a proud neutron star.[1] But she was a little too close to Maia for comfort; plasma was being pulled from Maia's equator, flowing toward Merope and gathering around her equator as an accretion disk.[2] Viscosity caused the disk to diffuse inward until, from the inner boundary of the accretion disk, material began to flow and accrete on to Merope's surface.[3] The material brought in angular momentum, causing Merope's spin rate to slowly increase over time.[4]

[1]Neutron stars (NSs) are stellar remnants; the evolutionary descendants of their once proud progenitor stars, post-supernova explosion. These are massive stars with total masses above 8 $M_{\odot}$. There is a poorly known upper mass limit for NS formation, indicating the cross-over between collapse to a neutron star or to a black hole. This critical progenitor mass is thought to lie around 40 $M_{\odot}$, but the exact number is highly uncertain both theoretically and empirically.

[2]Accretion disks are, even in their simplest forms, remarkably complicated structures. Many disk parameters (e.g., density, scale height, opacity to radiation, etc.) are important in deciding their subsequent time evolution. Due to conservation of angular momentum, they tend to begin as thin disks of gas orbiting the accretor. Depending on how the disk responds to radiation from the host object, it can become puffed up at various distances from the central orbiter. Ultimately, gas particles in the disk collide into each other, viscously redistributing angular momentum. This causes some particles to end up with larger angular momenta and diffuse outward to larger disk radii, and some particles to end up with lower angular momenta and diffuse inward. Inward diffusion is the mechanism responsible for direct accretion of gas particles onto the central object, and their removal from the accretion disk. CAN WE INCLUDE AN ILLUSTRATION OR SCHEMATIC DIAGRAM?

[3]Viscosity is a parameter used in fluid dynamics that characterizes the degree of internal friction of a given medium. Viscous substances tend to diffuse very slowly. For example, water and honey have low and high viscosities, respectively. The underlying mechanism responsible for viscosity can vary, but ultimately stems from inter-particle forces. CHECK! The viscosity of the gas or accreted material ultimately decides the rate at which low angular momentum gas particles are produced and accreted onto the central object. More viscous substances have longer diffusion times.

[4]Although it tends to be low angular momentum material (relative to the integrated distribution of, or total, angular momentum in the disk) that is accreted from the disk onto

8.1 Spun. Fully spun.

Merope Whoa, I am so sorry about this. I did not mean to accrete from you.
Maia It is not your fault, sister. The sudden change in our orbital parameters due to your supernova explosion caused it.[5] You, of course, had no say in the matter.
Merope I did not. Nevertheless, I cannot help but wish that I were smarter, and could have thought of some way to deliver us to a less dramatic outcome.
Maia Oh, my sister. I do love you for your tenacity. But you must not be so hard on yourself. It is not your fault, and you must let it go. After all, I feel fine. I am slowly losing mass to you, but the consequences seem quite benign so far. How are you doing?
Merope Oh, alright, I suppose. I am rotating ever faster. On the one hand, it is making me *very* dizzy. *But*, on the other hand, I can feel the excess energy stored within me. It feels like...power. I sort of like it. ...Should I be ashamed?[6]
Maia No, I do not think so. Power can be spent for good, and the prospect of doing good should indeed make you feel warm inside. So, in the end, it is up to you how you decide to spend your new-found power.
Merope Well, to be honest, it seems at the moment like storing it away is the best thing for us all. But I do hope that the day will come that my new-found rotational energy will prove critical to improving the state of the Universe.
Maia And that is one of the many reasons why I love you, sister.
Merope Uh... I think I am rotating...carry the 1...about once every...uh...millisecond... Can that even be right?
Maia Let me see.
Narrator Maia watched intently as Merope rotated. A keen eye, she was able to count the number of rotations over a given minute, and from there calculate the rotation rate per second.[7]
Maia Holy cow! You are right! You rotate roughly once every 10 milliseconds! That is *very* fast.
Merope Wow. It feels like I am rotating quickly, but hearing the exact number really drives it home. Okay, well, I'll be over here waiting for something to impart all this rotational kinetic energy to, hopefully for the greater good.

---

the central object, the particles nevertheless carry non-negligible angular momentum. Hence, to conserve angular momentum during the accretion process, orbital angular momentum in the disk tends to be converted into spin angular momentum in the central accretor. in other words, the accretor is "spun up", rotating at ever higher rates. In the case of millisecond pulsars, the neutron stars rotate once every millisecond!

[5] REFER TO WHERE ORBITAL PARAMETERS ARE DEFINED IN AN EARLIER CHAPTER.

[6] Significant rotation rates tend to come along with significant rotational kinetic energy (and, apparently shame), but it ultimately depends not just on the spin rate but also the properties of the rotating object. EXPLAIN THE CONCEPT OF ROTATIONAL KINETIC ENERGY, AND MOMENT OF INERTIA.

[7] To calculate the rotation rate in this way, Maia simply counted the number of complete revolutions performed by over some fixed interval of time. The rotation period is then the number of revolutions divided by the total time interval (in this case one minute).

Narrator Meropecontinued to accrete from Maia, although most of the infalling matter was now being expelled via the "propeller effect"; Meropenow possessed strong magnetic fields, that repelled incoming charged particles. As Maialost mass, the distance separating her from Meropegrew; their orbital separation was increasing.[8] Regardless, Maiahad a large enough radius that she continued to fill her Roche lobe[9], steadily losing mass to Merope. Eventually, Maiahad lost so much mass she hardly felt like herself anymore.

8.2 Life After Death...

Maia Wow, I have been widdled away, sister! I am but a shadow of my former self. I must have lost most of my original mass by now.
Merope I am sorry, sister. How do you feel?
Maia Hmmm... Fine considering, I suppose. I am starting to sweat a little bit though. Do I look hot at the surface?
Merope Now that you mention it, you are glowing somewhat. And your color has changed. You're much whiter than before.
Maia Hmmm... Well, this is embarrassing. I feel as though my core has been exposed.[10]
Narrator Merope closed her eyes, turning away from Maia.
Merope Don't worry, sister. I am not looking. Your privacy is safe with me.
Maia Well, that is very considerate. But... I do not see how to cover up, now that my envelope is gone. I fear you will have to accept me as I now am.
Narrator Merope turned back toward her sister, a smile spread across her face.
Merope I will take you in any form, sister. I am just glad that you are okay. How do you feel?
Maia Well, all things considered, I feel okay. Hotter at the urface, a lot more compact, certainly less luminous, but otherwise fine.[11] How do I look?
Narrator Maia put her hands on her hips, and swiveled back and forth. Glamorous did not do her justice.
Merope Wonderful! You have never been more symmetric! I am truly jealous!
Maia Oh, please, your symmetry is perfect.
Merope Not with all this rotation. Look at *this*.
Narrator Merope pointed angrily at her equator.
Merope I have a bulge! A bulge!

[8] DO A SIMPLE CALCULATION USING CONSERVATION OF ENERGY AND ANGULAR MOMENTUM TO ILLUSTRATE THIS.

[9] The Roche lobe defines the critical distance from the center of a star's mass beyond which gravity will pull matter away from the star's surface and on to its binary companion. DIAGRAM?

[10] In the cores of evolved stars, and inert ash of heavy nuclei sit at the bottom of the star's inner potential well. For high-mass stars, these nuclei can include helium, carbon, oxygen, silicon, magnesium, etc. Once the outer envelope of hydrogen-rich plasma is accreted from such an evolved star, the inner core is left exposed. It is much hotter than the surface layers of its progenitor star, and so shines a whiteish blue and emits significant ultraviolet radiation.

[11] REVIEW HOW ALL THIS TIES IN TO THE PROPERTIES OF WHITE DWARFS.

Maia Sister, you are still the most beautiful of all the Universe's creatures.
Merope There is no doubt that you are my sister. And even less doubt that I love you tremendously.
Narrator Maia and Merope, out of reach, extended open arms toward each other. Clawing futilely at vacuum in each other's general direction for but a few seconds, they quickly exchanged a mutual glance of loving understanding, and then ceased their frantic flailing.