Balance within a star

This lesson is about the balance between gravity and nuclear fusion within a star

DynaLearn level 4 | Version 1.0
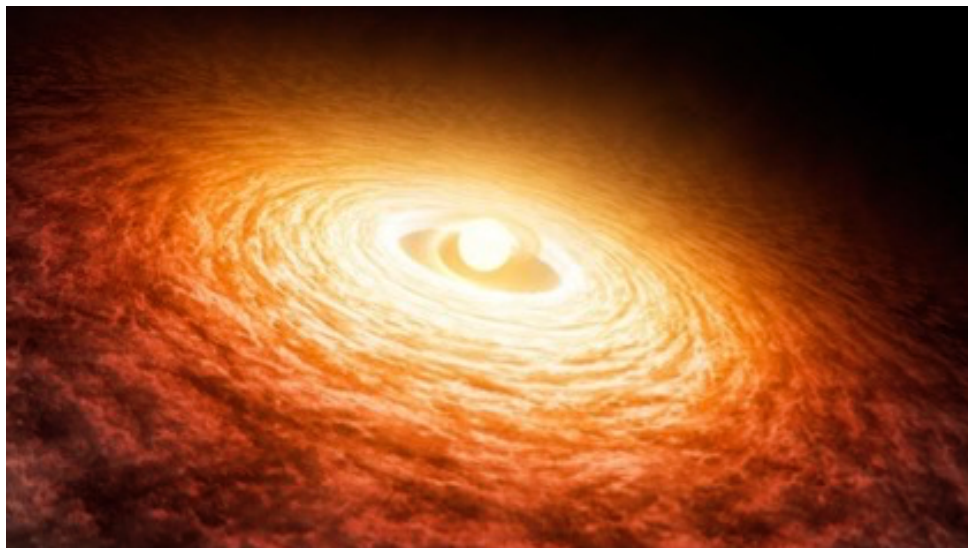

Figure 1. A young star with an accretion disk.

Summary
This lesson is about the formation of a star and how a star achieves a balance between gravity and nuclear fusion during this process.

Given name	
Surname	
Class	
Date	
Comments by teacher:	

Starting DynaLearn

There are several ways to log in. Use one of the two options below. Then check whether the login was successful (see 'Let's check!').

Via a code:

1. Go to DynaLearn (https://create.dynalearn.nl/).

2. Click on 'log in with code', at the bottom left.

3. Enter the project code and your (school) email address.

4. Copy the code from the sender's confirmation email dynalearn.nl (see spam folder) and fill in the other details.

5. Log in to DynaLearn.

By invitation:

1. Copy the login code from the sender's invitation email dynalearn.nl.

2. Go to DynaLearn (https://create.dynalearn.nl/).

3. Log in to DynaLearn.

Let's check!

After logging in, you will automatically enter the workspace of the assignment. You can recognize it by the gray question mark on the right side of the screen ⓘ. Is the question mark missing? Then first:

- In DynaLearn, click 🗋. Click on 'Select norm model'.
- Choose 'Fusion-gravity balance' and press 'Load'.

Save your model and start:

1. Click on 🏷 top left. Change the name to 'Fusion-gravity balance' and click 'Save'.

2. How do you proceed? Follow the steps in this workbook. Note! You can't skip steps. Ask for help if you get stuck. The video function 🎥 in DynaLearn shows how a model ingredient can be made. The boxes contain a brief explanation about the model ingredient. Put a check mark √ next to the step you performed. This way you keep track of where you left off.

1. Mass and gravity

You are first going to make the connection between the mass and gravity of the star in the model. The mass of a star causes gravity. If the mass increases, then the gravity also increases.

1. Read Box 1.


Box 1. Entity and quantity

An entity ⊗ is usually a physical thing in a system (e.g., car, human).

A quantity ⊙ is a measurable property of an entity (e.g., temperature, length).

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2. Create the entity *Star* (see 🎥 → ⊗).

3. Add the quantity *Mass* to the entity *Star* (see 🎥 → ⊙).

4. Add the quantity *Gravity* to the entity *Star.*

5. Read Box 2.

Box 2. A proportional relationship

In a proportional relationship, a change in one quantity **causes** a change in another quantity (the effected). In DynaLearn, **positive** and **negative proportional** relationships between quantities can be added and are labelled ⓟ⁺ and ⓟ⁻ respectively.

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6. The relationship between *Mass* and *Gravity* is **proportional**. Create this relationship (see

   🎥 → 📶). Check that the direction of the arrow is correct (cause → effect).

7. Is your diagram a bit messy and difficult to read? Click on ⚡ to align everything neatly. Click on ⤢ to make your model fit your screen. Use these buttons regularly.

8. Read Box 3.

Box 3. Help function

If the question mark ❓ or an ingredient in your model ⊗ is red, then something is wrong.

Click the question mark ❓ for a hint. Then click on a number, for example ① to see where the error is in your model. Only use the question mark if you can't figure it out yourself!

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9. Try out the help function by making a mistake in your model. Click ❓ to see the message. Fix the error.

10. Read Box 4.

Box 4. An exogenous influence.

If you want a quantity to decrease, remain stable or increase throughout the simulation, you must add an external influence to the quantity (an exogenous influence).

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11. Set the initial value: a **decreasing** exogenous influence for *Mass* (see 🎥 → 〜). This is because we have not yet established in the model **what** influences mass.

12. Read Box 5.

Box 5. Read the outcome of a simulation.

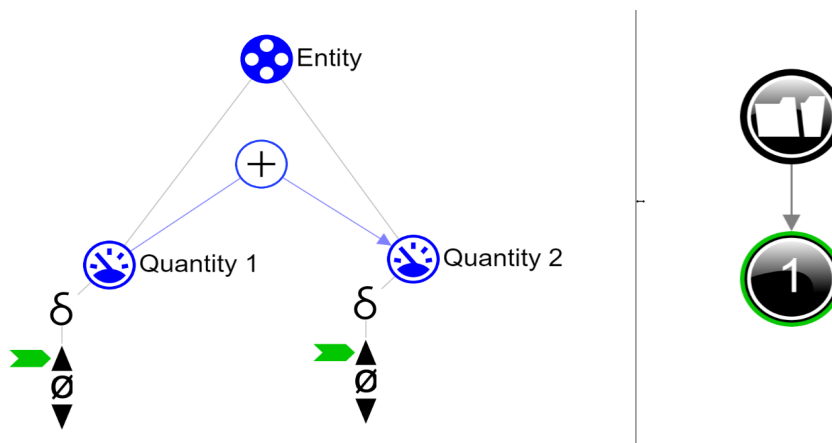After starting a simulation (with ⊘), a window appears on the right in which the possible states of the system are indicated. There is one possible state in this example ①.

You can click on the state to view the outcome. The state-icon then acquires a green edge. In the model, the change for this state is indicated by a green arrow ➤ . The model shows that in state ① Quantity 1 increases and that therefore Quantity 2 also increases.

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13. Start the simulation by clicking on: ⊘ (take note: there are two buttons for a simulation, use the right-hand button for a full simulation, see 🎥 → 🎞 from 1:00).

14. Read Box 6.

Box 6. Initial values

If initial values are **not** (or not properly) set, an exclamation mark appears after starting the simulation ⚠. If you click on it, a question appears, e.g., 'Delete initial value quantity?'. Click on the numbers, e.g., ①, to discover where something is not (correctly) set.

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15. Read the outcome of the simulation. What happens to gravity when mass decreases? Investigate what happens when mass stays the same or increases. To do this, change the exogenous (external) influence to **equal** and **increasing**. Describe below what cause-and-effect relationships take place (cross-out the incorrect answers):

If the mass decreases, then gravity *decreases/stays constant/increases*
If the mass stays constant, then gravity *decreases/stays constant/increases*
If the mass increases, then gravity *decreases/stays constant/increases*

16. Read Box 7.

> **Box 7.** Quantity space.
>
> A newly created quantity does not yet have a Quantity space. By adding a Quantity space you can indicate which values a quantity can take on. A Quantity space consists of points (⬤) and intervals (▮).
>
> - A point value is only one value. For example, a *boiling point*. A special point is the zero point, for which there is a separate symbol (Ø) in DynaLearn.
>
> - An interval is a set of values. The liquid phase of a substance is an example of an interval. In the case of water, the interval 'liquid' contains all values between 0 °C and 100 °C. The values 0 °C and 100 °C are respectively the 'melting *point*' and the 'boiling *point*' between which the interval 'liquid' is located.

17. Create a quantity space (see → ☰) with two values for the properties *Mass* and *Gravity* (if necessary, use the help function, see Box 3):
    i. **+** (*upper range*)
    ii. **Ø** (*point*)

18. The current model in DynaLearn is not yet precise enough. This is evident from the following simulation. Set the following initial values (select the item and click on ➤, see → ➤):
    i. Both quantities are positive (+)
    ii. *Mass* decreases with an exogenous influence, so (see → 〰).

    Start the simulation. The simulation gives 3 states. Which states are physically correct?

    States:

The model is not yet accurate. If there is mass, there is also gravity and if there is no mass, there is no gravity. The model needs to link these properties together. The next step explains how to do this.

19. Read Box 8.

> **Box 8.** Correspondence.
>
> In a system, it can happen that certain values of different quantities can only occur together. You can then make a **correspondence** between the value ranges of both quantities. In the model, you can make a **correspondence** between these values. It can also happen that **all** the values of a range of values of one quantity correspond to all the values of a range of values of another quantity. You can then make a correspondence between the **range of values** (i.e., instead of between the individual values) of both quantities.

20. Create a **directed correspondence** (see ▇ → ⬒) between the quantity space for *Mass* and *Gravity*. Leave the initial values as they were in the previous step.

21. Click on ⚡ to align the model. Click on ⤢ to make your model fit the screen.

22. Start the simulation. How many states are possible now?

Number of states:

23. Read Box 6 (again).

> **Box 6.** Initial values
>
> If initial values are **not** (or not properly) set, an exclamation mark appears after starting the simulation ⓘ. If you click on it, a question appears, e.g., 'Delete initial value quantity?'. Click on the numbers, e.g., ❶, to discover where something is not (correctly) set.

24. Describe the results of the simulation (cross out the incorrect answers):

State 1.
The star *has/does not have* mass as the value is *0/+.* The mass *decreases/stays constant/increases*. The star *has/does not have* gravity as the value is *0/+.* The gravity *decreases/remains constant/increases*.

State 2.
The star *has/does not have* mass as the value is *0/+.* The mass *decreases/stays constant/increases*. The star *has/does not have* gravity as the value is *0/+.* The gravity *decreases/remains constant/increases*.

25. Read Box 9.

> **Box 9.** Progress bar
>
> At the bottom of the screen is the *progress bar* (see example below). For each ingredient, the progress bar displays (i) how many of this type have already been created, (ii) how many need to be created in total, and (iii) how many are currently incorrect in the model.
>
> In the example below: (i) 1 quantity 🕹 has been created, (ii) 4 quantities need to be created in total, and (iii) there are no incorrectly created quantities. The created quantity space (▇) is not correct as the last number is displayed in red. As soon as, for a given type of ingredient, the required number have been correctly placed in the model, all of the numbers for this ingredient will turn green, as for entity 🎞 in the example.
>
> 🎞 1/1/0   🕹 1/4/0   ⊙ 0/4/0   ① 1/4/**1**   ⬒ 0/1/0   Ⓟ 0/1/0   Ⓘ 0/2/0   # 2/13

2. Gravity and density

A star forms from a cloud of gas, consisting mainly of hydrogen atoms. Gravity 'pulls' these atoms ever closer to the centre of the forming star. As a result, the distance between the atoms decreases and the density of the gas increases. A structure becomes spherical (see Figure 2).
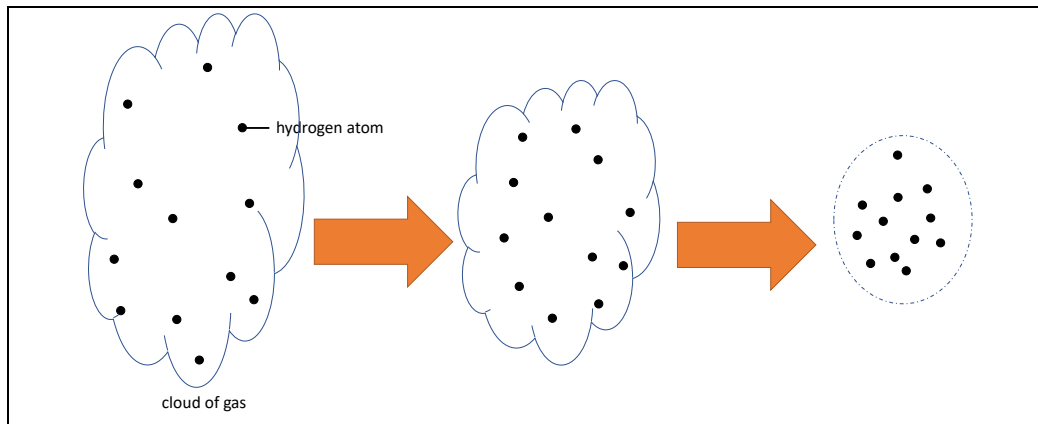
Figure 2. The density of the hydrogen atoms increases.

Earlier in the lesson you learned that the relationship between *Mass* and *Gravity is* **proportional**. The relationship between *Gravity* and *Density* is **not** proportional. Gravity acts as a process.

1.   Answer the question below (cross out incorrect answers):

> When gravity **remains constant** the density of the star will *decrease/remain constant/increase.*

2.   Read Box 10.

Box 10. An influence relationship.

Some quantities in a system are processes. A process is a quantity that adds or removes something to the system **per unit of time** (e.g., per second, per year). Typical examples of processes that **add** something are: (i) water from a tap that flows (L/s) into a bath, (ii) an oven that provides a certain power (J/s) to heat a dish, and (iii) the amount of tax paid every year (€/y). The outflow (L/s) of water through a drain is an example of a process that **removes** something from the system.

The relationship between a process and another quantity is called an **influence** ($(I+)$ or $(I-)$). In this type of relationship, the **value** of the process determines the **change** in the quantity on which an influence is exerted.

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3.   Create the quantity *Density* connected to the entity *Star*. This quantity does not require a value range.

4.   Create the relationship between *Gravity* and *Density* (see 📷 → 🎚️).

5.   Click on [⚡] to align the model. Click on [↙↗] to make the model fit to the screen.

6.   Set the initial values as follows:
    i.   *Mass* is positive (+)
    ii. *Mass* remains constant (with an exogenous (external) influence)

7. Simulate the model and describe the results (cross out the incorrect answers):

State 1.

The star *has/does not have* mass because its value is w*0/+.* The mass *decreases/remains constant/increases*. The star *has/does not have* gravity because its value is *0/+.* The gravity *decreases/remains constant/increases.* Because of this, the density of the star *decreases/remains constant/increases.*

3. Accretion

The star is created from a large cloud of gas in space, referred to as nebula. As you saw in the previous section, such a cloud of gas slowly but surely collapses under its own gravity. The star will form in the centre of the nebula, where eventually most of the mass of the nebula clumps together and the highest density is reached. The mass of the star thus increases as particles from the gas cloud 'fall' on it. We call this process *accretion*.

1. Create the entity *Nebula*.

2. Create the quantity *Accretion* for the entity *Nebula*.

3. Create a quantity space for the quantity *Accretion*:
   i. **+** (*upper interval*)
   ii. **Ø** (*point*)

4. Create the relationship between *Accretion* and *Mass*. Check the direction of the relationship carefully!

5. Click on 🔲 to align the model. Click on 🔲 to fit the model to the screen.

6. Set the initial values:
   i. Remove the external influence for *Mass*
   ii. *Accretion* is positive (+)
   iii. *Accretion* remains constant (with exogenous influence)
   iv. *Mass* is zero (Ø)

Note: *the assumption that the mass is zero is not completely correct. In reality, the star forms in the core of the nebula. At the moment the collapse of the cloud starts (i.e., accretion takes place), the star already contains some material. For convenience, however, you may assume that the nebula and the star are separate, and so the mass of the cloud overflows into an 'empty' star.*

8. Simulate the model and describe the results (cross out the incorrect answers):

> State 1.
>
> Accretion is *0/+* so the *nebula does/does not* collapse. The star *has/does not have* mass and gravity because these values are *0/+.* This results in the density *decreasing/remaining constant/increasing.*
>
> State 2.
>
> The star *has/does not have* mass and gravity as these values are *0/+.* This results in the density *decreasing/remaining constant/increasing.*

4. Mass of the nebula

Most of the mass in the nebula ends up in the star.

1. Create the quantity *Mass* for the entity *Nebula*.

2. Create a quantity space for the quantity *Mass*:
    i.   **+** (*upper interval*)
    ii. **Ø** (*point*)

The accretion of the nebula onto the star causes a **decrease** in the mass of the nebula. This decrease is a process.

3. Answer the following question (cross out the incorrect answers):

> When accretion is remains **constant,** the mass *of the nebula decreases/remains constant/increases.*

4. Create the relationship between *Accretion* and *Mass* for the entity *Nebula.* Check the direction of the relationship carefully!

There is also a relationship between *Mass* and *Accretion* (i.e., in the opposite direction to the above question). If the mass of the nebula decreases then the accretion decreases. Note! This is a *positive proportional* relationship because both quantities change **in the same direction**.

5. Create the relationship between *Mass* and *Accretion* for the quantity *Nebula.* Check the direction of the relationship carefully!

6. Create a **directed correspondence** (see 🎥 → ⚏) between the quantity spaces for *Mass* and *Accretion* for the entity *Nebula.*

7. Click on [⚡] to align the model. Click on [⤢] to fit the model to the screen.

8. Set the initial values:
    i.   Remove the initial value for *Accretion* (remove the blue arrow next to +)
    ii. Remove the exogenous influence for *Accretion.* There is now no need for an external influence. The relationship between *Accretion* and *Mass* creates feedback and determines the change in the *Mass* of the quantity *Nebula.*
    iii. *Mass* of the quantity *Nebula* is positive (+).
    iv. Do not change the other initial values set in previous sections.

9. Simulate the model and describe the results (cross out the wrong answers):

> State 1.
> The nebula *has/does not have* mass. There *is/is no* accretion from the cloud. The mass of the nebula *decreases/remains constant/increases.* The mass of the star is *0/+* and *decreases/remains constant/increases.*
>
> State 2.
> The mass of the star is *0/+* and *decreases/remains constant/increases*.
>
> State 3.
> The nebula *has/does not have* mass. There *is/is no* accretion from the nebula. The mass of the nebula *decreases/remains constant/increases.* The mass of the star is *0/+* and *decreases/remains constant/increases.*

5. Fusion

If the density in the centre of the nebula (proto-star) continues to increase, then at some point the hydrogen particles get so close together that nuclear fusion is initiated. In this process, four hydrogen particles gradually melt together to form one helium nucleus. During this process, energy is released in the form of light, among other things. Figure 3 shows how hydrogen particles fuse into a helium nucleus (aka the proton-proton sequence). The exact details of Figure 3 are not a subject of this lesson.
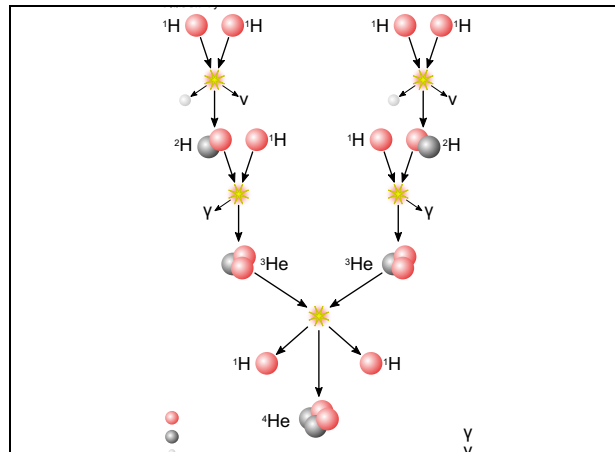

Figure 3. Nuclear fusion of hydrogen to helium in a star.

1. Create the quantity *Fusion* for the entity *Star*.

2. Create a quantity space for the quantity *Fusion*:
    i.   **+** (*upper interval*)
    ii.   **Ø** (*point*)

3. Create the relationship between *Density* and *Fusion.* Check the direction of the relationship carefully!

4. Click on ⚡ to align the model. Click on ⤢ to fit the model to the screen.

5. Set the initial values:
    i.   *Fusion* is zero (Ø)
    ii.   Do not change the other initial values set in previous sections.
    Start the simulation.

6. Describe the results of the simulation (cross out the wrong answers):

> State 4.
>
> The gravity of the star is *0/+* and *decreases/remains constant/increases*. The density of the star *decreases/remains constant/increases.* The fusion of the star shall therefore *decrease/remain constant/increase.*

The model is not yet complete. In reality, fusion will not continue to increase! The nuclear fusion is resisting the further collapse of the star, so the density eventually stops increasing. This is because the energy released by nuclear fusion creates a counteracting force (Figure 4). A balance is created in the star.
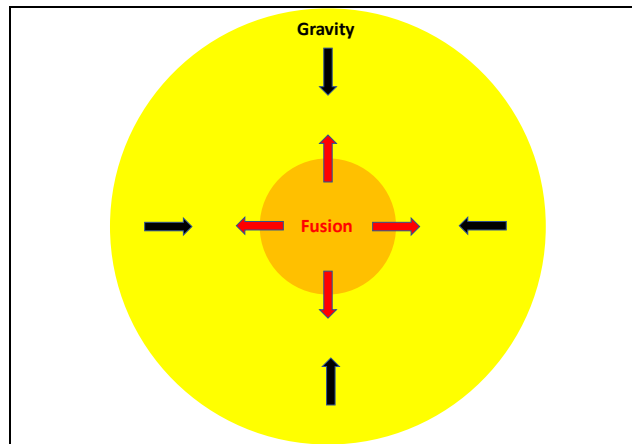
Figure 4. Balance between fusion and gravity in a star.

7. Create the relationship between *Fusion* and *Density* (in the opposite direction to that created in question 3).

8. Read Box 11.

> **Box 11.** An (in)equality
>
> An inequality (<, ≤, ≥, >) can indicate which values of two quantities are initially the largest (e.g., A < B). You can also indicate that both values are initially equal (=) with an equality. Note! this concerns the **initial** (in)equality, i.e., at the beginning of the simulation. This can change over the course of the process.

9. Set the initial values:
    i.   Create an equality between *Gravity* and *Fusion* (see 🎥 → ⊜). So, gravity and fusion initially have an equal influence on the density.
    ii. Do not change the other initial values set in previous sections.

10. Simulate the model and describe the results (cross out the wrong answers):

State 1.
The gravity of the star is *0/+* and the fusion is *0/+.* Both processes *are/are not* in balance and as a result, the density *decreases/remains constant/increases.*

State 2.
The gravity of the star is *0/+* and the fusion is *0/+.* The influence of gravity is *less than/equal to/more than* the influence of fusion. De density and fusion *decrease/remain constant/increase.*

State 3.
The gravity of the star is *0/+* and the fusion is *0/+.* The influence of gravity is *less than/equal to/more than* the influence of fusion. De density and fusion *decrease/remain constant/increase.*

State 4.
The mass of the star is *decreases/remains constant/increases* and therefore the gravity *decreases/remains constant/increases.* The influence of gravity is *less than/equal to/more than* the influence of fusion. De density and fusion *decrease/remain constant/increase.*

State 5.
The influence of gravity is *less than/equal to/more than* the influence of fusion. De density and fusion *decrease/remain constant/increase.*

After the star reaches equilibrium (when gravity and fusion are in balance), the star starts to shine due to the light released during nuclear fusion. This then causes accretion from the nebula to stop: the remaining gas particles in the gas cloud are 'blown away' by the star's light. The formation of the star is complete.

In some cases, accretion stops earlier, because the mass in the nebula 'runs out' before the star starts to shine. When this happens, the star does not have enough gravity to reach a density high enough for nuclear fusion. The star then fails to radiate. Such a 'failed' star is called a brown dwarf.

6. Mass to the protoplanetary disk

Not all of the mass in the nebula goes into the formation of the star. A small fraction ends up in orbit around the young star and becomes the protoplanetary disk (see Figure 1 on page 1). There is not enough mass in the protoplanetary disk for nuclear fusion to occur.

1. Create the entity *Protoplanetary disk*.

2. Create the quantity *Mass* for the entity *Protoplanetary disk*.

3. Create a quantity space for the quantity *Mass* for the *Protoplanetary disk*.
   i. **+** (*upper interval*)
   ii. **Ø** (*point*)

The accretion of the gas cloud causes an increase in mass in the protoplanetary disk. This increase is a process.

4. Create the relationship between *Accretion* and *Mass* for the entity *Protoplanetary disk*. Check the direction of the relationship carefully!

5. Click on ⚡ to align the model. Click on ⤢ to fit the model to the screen.

6. Set the initial values:
   i. *Mass* of the entity *Protoplanetary disk* is zero (Ø)
   ii. Do not change the other initial values set in previous sections.

7. Simulate the model and describe the results (cross out the wrong answers):

State 1.
The nebula *has/does not have* mass. There *is/is no* accreting. The mass of the nebula is *decreasing/remaining constant/increasing*. The mass of the protoplanetary disk is *0/+* and *decreases/remains constant/increases*.

States 2 and 3.
The mass of the protoplanetary disk is *0/+* and is *decrease/remains constant/increases*.

States 4 and 5.
The nebula *has/does not have* mass. There *is/is no* accreting. The mass of the nebula is *decreasing/remaining constant/increasing*. The mass of the protoplanetary disk is *0/+* and *decreases/remains constant/increases*.

The protoplanetary disk continues to rotate around the newborn star. The gas and dust particles clump together, creating a higher density in some places in the disk. As we saw earlier, such a spot collapses under its own mass into a sphere. Eventually, this creates (gas) planets. Planets are not massive (heavy) enough to achieve nuclear fusion. Smaller objects can also form, such as asteroids.

The planets are, as it were, a 'by-product' of the star's formation. It is therefore not surprising that astronomers have already discovered thousands of so-called 'exoplanets' (planets orbiting a star other than the sun): it is quite normal for stars to have planets.