Qualitative Models to learn about Star Properties, Star States, and the Balance between Fusion and Gravity

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Abstract

This paper presents three qualitative models that were developed for the Stargazing Live! program. This program consists of a mobile planetarium that aims to inspire and motivate learners using real telescope data during the experience. To further consolidate the learning experience three lessons are available that teachers can use as follow up activities with their learners. The lessons implement a pedagogical approach that focuses on learning by creating qualitative models with the aim to have learners learn subject specific concepts as well as generic systems thinking skills. The three lessons form an ordered set with increasing complexity and were developed in close collaboration with domain experts.

1 Introduction

Star formation, stellar properties and the underlying physical laws are fundamental topics in pre-university physics education. However, learning about stars can be challenging for learners, due to a variety of pre-instructional conceptions and learning difficulties. For example, learners often do not know that nuclear fusion provides stars with their energy, allowing them to generate light [1,3]. In addition, they have an incomplete understanding of how stars are formed. When asked how stars differ from each other, learners often mention properties such as size or composition, but less often luminosity, temperature, or lifespan. For example, in Bailey and colleagues' study [2], only 21 of 381 learners named mass as a property that distinguishes stars. Previous research shows that traditional instruction in astrophysics courses is not always sufficiently effective and that there is a need for interventions that stimulate conceptual understanding [3].

The Stargazing Live! project [11,12] uses a mobile planetarium to bring semi-live real scientific astronomy data into the classroom. Planetariums have played a role in the learning of astronomical concepts since their inception [4]. They can provide a unique and enriching learning experience [14] and spark learners interest and excitement for astronomy [16, 13] and help improving retention [19].

Key requirements for an effective learning experience in a planetarium is that viewers are allowed and encouraged to ask questions, participate in simulations, and engage in hands-on activities to deepen their understanding of the concepts [16, 17, 13]. The combination of planetarium and traditional classroom lessons can provide a well-rounded education experience that complements and reinforces each other [14, 15].

To address these issues, the Stargazing Live! program comprises two parts. First, learners are introduced to the idea of the changing universe and associated astronomy concepts during a live and interactive planetarium experience. Shortly thereafter, learners further develop and consolidate their knowledge with lesson activities during which they create and simulate cause-and-effect models using computer-supported modelling software. By constructing a model of a system, learners develop a deeper understanding of its underlying principles and relationships between components. This process helps to build and refine their conceptual model, providing a clearer and more comprehensive understanding of the system [8, 9]. Moreover, constructing a model requires active engagement, as learners think deeply about the information and make connections to their prior knowledge. This form of active learning, where learners are actively involved in the learning process, has been shown to be more effective than passive forms of learning [18].

Three qualitative models were created to serve as a basis for the three *learning by modelling* lessons that the Stargazing Live! program developed. The lessons form an ordered set with increasing complexity. The first lesson, *star properties*, focuses on learners identifying key quantities that characterize stars and establishing the causal dependencies between them. The second lesson, *star states*, follows on from the star properties assignment by adding ranges of qualitative values (represented in quantity spaces) to six key quantities. During this assignment learners learn how stars can be classified according to mass and how that relates to characteristic values for other quantities. The third lesson, *fusion-gravity balance*, focusses on the birth of stars and how a balance emerges between the gravitational force (inwards) and the nuclear fusion force (outwards).

The organization of this paper is as follows. Section 2 describes the planetarium experience. Section 3 introduces the DynaLearn software that was used to create the models for the lessons. Section 4, 5 and 6 each describe one of the three models. Section 7 concludes the paper.

2 Planetarium experience

The planetarium experience has been developed by NOVA (Netherlands Research School for Astronomy) using a Mobile Planetarium (Fig. 1). The semi-live real data are taken from the small optical telescopes MeerLICHT (www.meerlicht.org) and BlackGEM (www.blackgem.org), both operated by Radboud University in the Netherlands. MeerLICHT is stationed in South Africa and performs optical follow-up for the MeerKAT radio telescope. The BlackGEM array is in La Silla, Chile and currently comprises three telescopes. Data from the telescopes are uploaded each night, processed automatically, and made available for use within 20 minutes. To run the lessons the mobile planetarium uses customized scripts in the Digistar 6 software.

Figure 1. The planetarium experience.

The topic of the Stargazing Live! program is ‘the changing universe’ and discusses a range of transient phenomena in the night sky including (near Earth) asteroids, variable stars, (super)novae and gravitational wave events, such as kilonovae. Each topic is introduced with a discussion around a data set from the telescopes projected onto the correct region of the sky in the planetarium software. Learners are asked to identify changing features in the images and think about what they might be seeing. The various physical processes at work are then explained using custom-made 3D-visualisations and animations. Key curriculum topics for pre-university level astrophysics are also included such as an explanation of how Wien’s law connects stellar surface temperature to the observed colour of an object and how the luminosity of a star is related to other measurable parameters.

3 DynaLearn – Learning by representing

The modelling lesson activities within the Stargazing Live! program use the DynaLearn software (https://dynalearn.eu) [6]. This software provides a qualitative vocabulary to represent conceptual models [10]. No quantitative information is used. Instead, logic-based algorithms are used to generate simulations [5]. Models built in DynaLearn can be represented at multiple levels of complexity [6]. Higher levels use a richer vocabulary to express the system and its behaviour. At each level, the software has scaffolds to support learners during their knowledge creating effort. The *norm-based feedback* pinpoints errors made by learners (solving these remains a task of the learner). The *scenario advisor* inspects the status of the model before starting a simulation and automatically highlights missing initial settings as well inconsistent settings. The *progress bar* shows how many ingredients have already been created and how many still need to be created. The working of the software is partly explained in the workbook which guides learners through the assignments, but it is also provided from within the software [7].

4 Star properties (level 2)

Lesson activities were developed to extend the planetarium experience, focusing on key concepts in the Dutch secondary school physics curriculum. A specific request was to focus on conceptual understanding of star formation and star properties and the associated laws (e.g., Wien’s law and the Stefan-Boltzmann law).

The *star properties* model is shown in Fig 2. The model is created at level 2 of the software, which is relatively simple for learners in pre-university education. The complexity arises from the number of ingredients that need to be created and connected (26 modelling steps) combined with running various intermediate simulations with various initial values.

Entities are used to represent the objects (or parts) that together form the system. This model comprises three entities, Stars (the overarching object), the inner Core and the outer Surface. Two *configurations* specify that Stars have a Core and Stars have a Surface. *Quantities* represent the dynamic and measurable properties that characterize the stars and their behaviour. Eleven quantities are defined, such as Mass, Gravity, Fusion-energy, etc. *Causal dependencies* specify how the change of one quantity influences the change of another quantity. They can be positive, e.g., more Mass results in more Gravity, or negative, e.g., higher Fusion-energy results in a shorter Lifespan.

Initial settings are required to run a simulation. Mass is the quantity at the beginning of the causal chain and thus the only quantity for which an initial change must be specified. When Mass is set to change, the simulation shows how the remaining quantities change (green arrows in Fig. 3). As can be seen in Fig. 3, when Mass increases, all intermediate quantities also increase, and at the end of the causal chain, Radius and Luminosity also increase while Wavelength and Lifespan decrease.

A workbook is used to guide leaners during the lesson. The workbook presents the lesson in 5 steps, notably (a) Entity stars with two quantities (which focusses on Mass ad Gravity), (b) Properties of the core (which focusses on Pressure, Temperature and Fusion-energy, and how these are causally related as well as related to the quantities created in the first step), (c) Properties of the surface (which focusses on Temperature (of the Surface), Wavelength and Luminosity and how these are causally related as well as related to the quantities created before), (e) What else do we know? (which challenges learners to find and add the still missing quantities (namely Gas pressure, Radius & Lifespan) and their cause-and-effect relations. After each step. Learners are asked to run simulations and process the results (e.g., by answering questions).

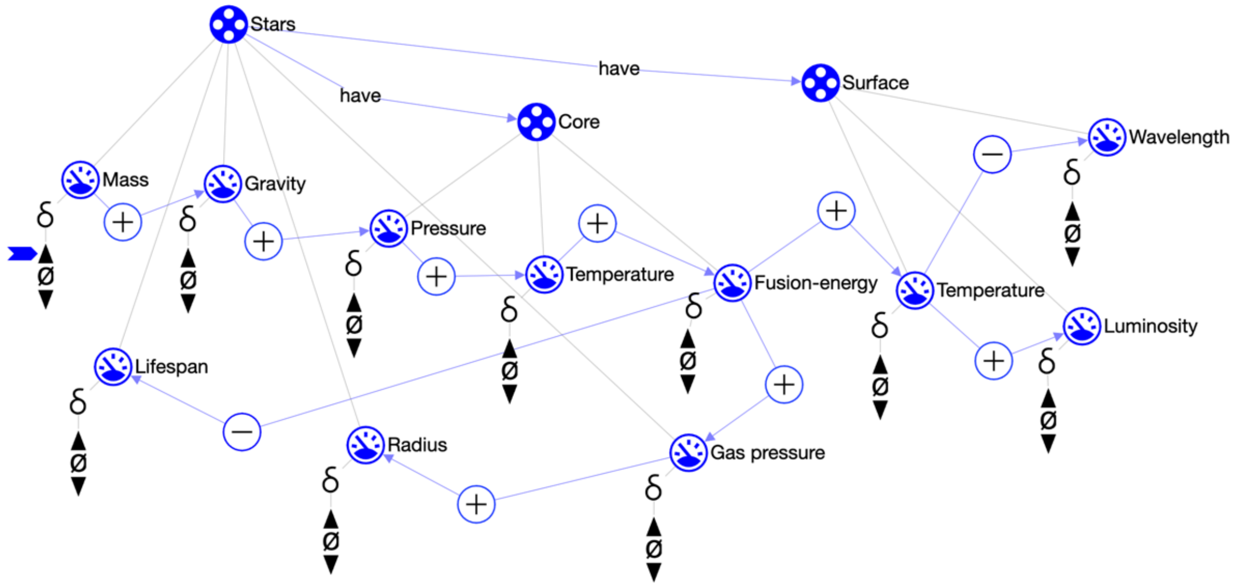

Figure 2. Star properties model with three entities (Stars, Core & Surface), two configurations (2x have), eleven quantities (Mass, Gravity, Pressure, Temperature (of the Core), Fusion-energy, Temperature (of the Surface), Wavelength, Luminosity, Gas pressure, Radius & Lifespan), and ten causal dependencies (2 negative & 8 positive). Mass is set to initially increase (blue arrow).

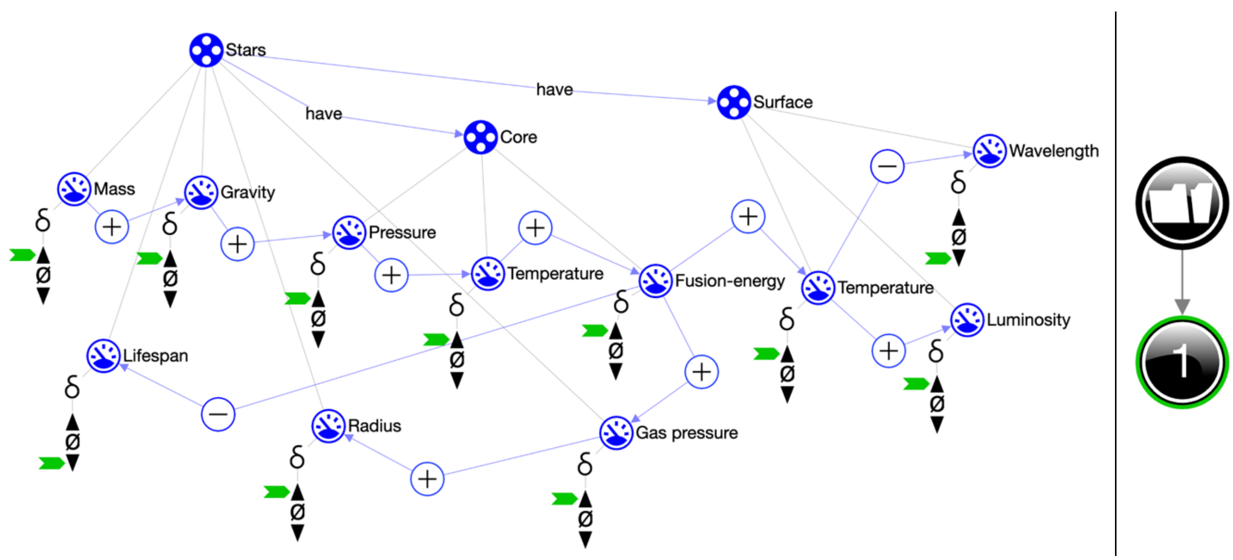

Figure 3. Simulation result for the star properties model shown in Fig. 2. Each quantity has a ∂ which can be decreasing (arrow down), steady (∅), or increasing (arrow up). Starting with Mass increasing, the simulation shows how other quantities change depending on their proportional relationship with the preceding quantity.

5 Star states (level 3)

The *star states* model (Fig. 4) is created at software level 3. New vocabulary at this level includes *quantity space* (a set of alternating point and interval values that the quantity can take on), *correspondence* (for representing co-occurring values among values from different quantity spaces), and *exogenous quantity behavior* (setting a quantity to keep decreasing, increasing, behave random, etc.) [5]. Correspondences can be directed (only when the source is known, the target can be calculated) or undirected (if one is known, the other can be calculated), and regular (the highest value of one quantity corresponds to the highest value of the other quantity, etc.) or inverse (the highest value of one quantity corresponds to the lowest value of the other quantity, and vice versa).

The *star states* model augments six key quantities from the star properties model with a quantity space, notably Mass, Temperature (of the Surface), Wavelength, Luminosity, Radius & Lifespan. However, to optimally fit the curriculum requirements Wavelength has been replaced by Peak wavelength and Peak colour. Each quantity space holds five values (three intervals separated by two points), and specific values correspond to quantities across the model. For instance, stars with Mass in the red dwarf region (less than 0.5 times the mass of the sun), have a (Surface) Temperature of less than 4000 K, a Lifespan of more than 10$^{\wedge 11}$ years, a Peak wavelength of more than 720 nm, etc.

Learners build the quantity space for each of the key quantities and specify how these values correspond across the model. The lesson is organised as follows. Learners start by creating the quantity space for Mass, run the simulation and discover that they need to apply an exogenous increase to the mass to have the simulation progress through the quantity space fully. Step 2 focusses on the quantity space for Lifespan, and that it inversely corresponds the quantity space of Mass (more Mass corresponds to shorter Lifespan, etc.). Step 3 focusses on Surface Temperature. Step 4 focusses on Peak wavelength and Peak colour simultaneously. Finally, step 5 focusses on Luminosity and step 6 on Radius.

To support learners in determining the values of the quantity spaces the workbook provides short descriptions of each phenomenon. Effectively, all the terms are mentioned in the workbook, but it still requires an effort on behalf of the learners. Specifically, deciding upon the correct terms, their order, and which value is lowest and which value is highest (bottom and top of the quantity space, respectively). Notice that, the norm-based support [7] helps the learners with this challenge. Once a quantity space is in place the next task for learners is to place the correct correspondence, both deciding upon which quantity spaces (of which quantities) to relate and whether the correspondence is regular or inversed.

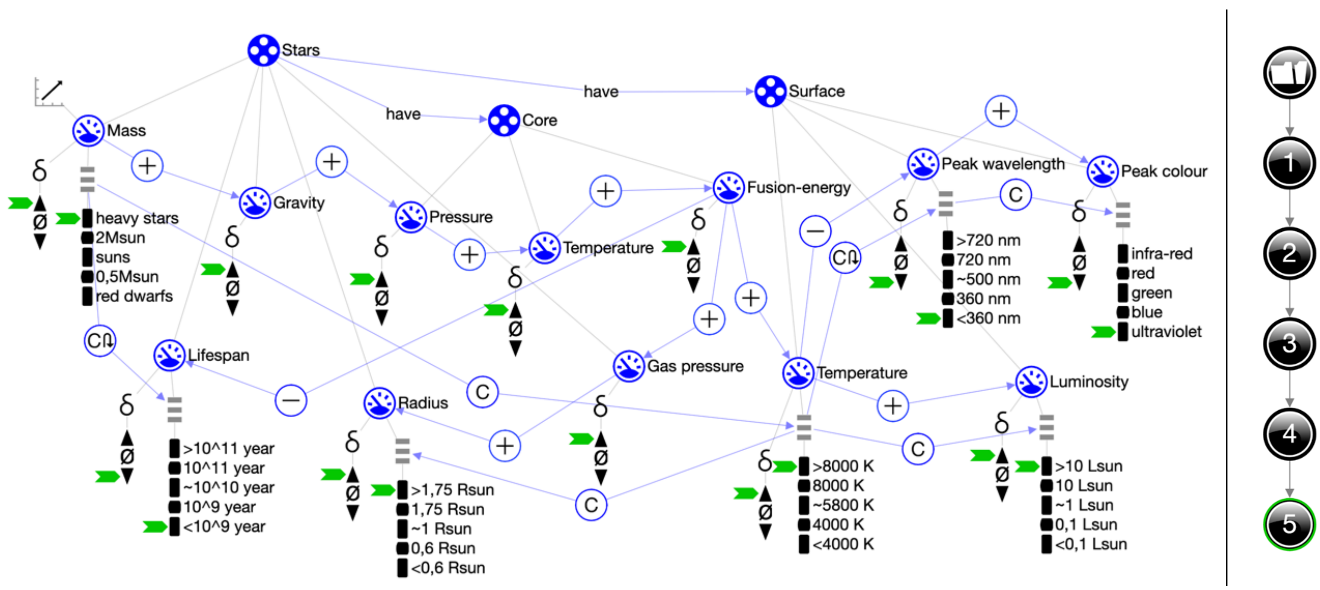

Figure 4. Part of the simulation results for the *star states* model. The simulation started with *Mass=<red dwarfs, +>* (not shown). Following this setting the six key quantities get their initial value via correspondences (C), notably, *Lifespan* started at *<10^9 year, Radius* at *<0.6 Rsun, Temperature* at *<4000 K, Luminosity* at *<0.1 Lsun, Peak wavelength* at *<360 nm,* and *Peak colour* at *infra-red*. The derivatives are calculated using the causal dependencies (–, +). The state-graph (RHS) shows that the simulation progressed through 5 states. State 5 is shown (LHS).

6 Fusion-gravity balance (level 4)

The goal of this *fusion-gravity balance* model is to represent the process of star formation and the consequential fusion-gravity balance that emerges. This model is therefore created at level 4 of the DynaLearn software (Fig. 5). This level introduces *influence* (I+/I–) and *proportionality* (P+/P–) [5,10] to distinguish between processes (I) (initial causes) and the propagation (P) of these through the system. Positive and negative *feedback loops* and *in/equality* (< ≤ = ≥ >) to represent the relative impact of competing processes.

The model starts by distinguishing three entities and their associated quantities: Nebula (Mass & Accretion), Star (Mass, Gravity, Density & Fusion) and Protoplanetary disk (Mass). The model assumes a certain amount of Mass being present in the Nebula <+, ?>, while other quantities are zero <0, ?> (Masses of Star and Protoplanetary disk, and Fusion) or unknown <?, ?> (Accretion, Gravity, and Density). Simulating the model delivers 5 states. Each state representing a unique qualitative behaviour of the system. Table 1 shows the details with for each quantity, in each state, specifying its value and direction of change, represented as a tuple <v, ∂>.

How are these results generated? It starts with the Accretion process, which corresponds (C) and is proportional (P+) to the Nebula's Mass (hence Accretion=<+, –>). Accretion negatively influences (I–) this Mass of the Nebula (hence Mass=<+, –>) and positive influences (I+) the Mass of the Star and the Protoplanetary disk (both <0, +>, see Table 1, state 1). Note that, as soon as Accretion becomes active, it is decreasing because Mass (of the Nebula) is decreasing.

The Gravity of the Star corresponds (C) and is proportional (P+) to the Mass of the Star (Gravity=<0, +>). The Gravity positively influences (I+) the Density, but being zero, has no effect yet in the initial state (state 1). Therefore, Density remains steady, and Gravity in balance with the (not yet active) Fusion (Gravity=Fusion). Note that, to keep the model simple, we choose to not define a quantity space for Density.

State 1 terminates into state 2 in which the Star accumulates Mass (Mass=<+, +>) and consequently the gravitation becomes active (Gravity=<+, +>). Now Density starts increasing and Fusion is about to start (Fusion=<0, +>), but momentarily not yet, therefore Gravity>Fusion.

State 2 progresses into state 3 in which the Fusion becomes active (Fusion=<+, +>), however Gravity still has a stronger impact, hence Gravity>Fusion. State 3 changes into state 4 in which all the Mass from the Nebula has been consumed (Mass=<0, 0>). The Accretion stops (Accretion=<0, 0>) and the Mass of the Star and the Protoplanetary disk stabilise (hence, both <+, 0>). However, Gravity remains active (Gravity=<+, 0>), still outperforms Fusion (Gravity>Fusion), and therefore Density keeps increasing. In state 5 the Fusion catches up with the Gravity and the processes balance (Gravity=Fusion) and the Density stabilises. Fig. 6 shows the simulation results for this final state.

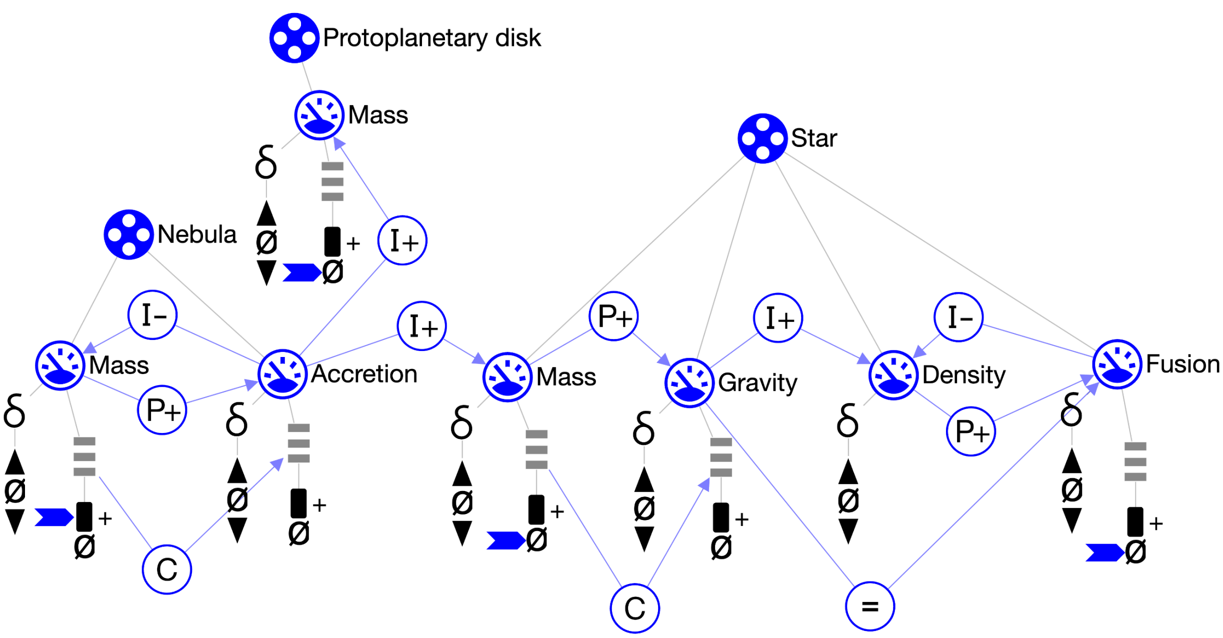

Figure 5. The *fusion-gravity balance* model and its initial setting. The model assumes a certain amount of Mass being present in the Nebula <+, ?>, while other quantities are zero <0, ?> (Masses of Star and Protoplanetary disk, and Fusion) or unknown <?, ?> (Accretion, Gravity, and Density). Note that in this starting state, Gravity=Fusion. In fact, both are still non-existing.

Table 1. Simulation results for the *fusion-gravity balance* model. Quantities have a value and a direction of change, represented as <v, ∂>.

	Nebula		Proto. disk	Star				
State	**Mass**	**Accretion**	**Mass**	**Mass**	**Gravity**	**Density**	**Fusion**	**Gravity ? Fusion**
1	<+, –>	<+, –>	<0, +>	<0, +>	<0, +>	<?, 0>	<0, 0>	Gravity = Fusion
2	<+, –>	<+, –>	<+. +>	<+, +>	<+, +>	<?, +>	<0, +>	Gravity > Fusion
3	<+, –>	<+, –>	<+. +>	<+, +>	<+, +>	<?, +>	<+, +>	Gravity > Fusion
4	<0, 0>	<0, 0>	<+. 0>	<+, 0>	<+, 0>	<?, +>	<+, +>	Gravity > Fusion
5	<0, 0>	<0, 0>	<+. 0>	<+, 0>	<+, 0>	<?, 0>	<+, 0>	Gravity = Fusion

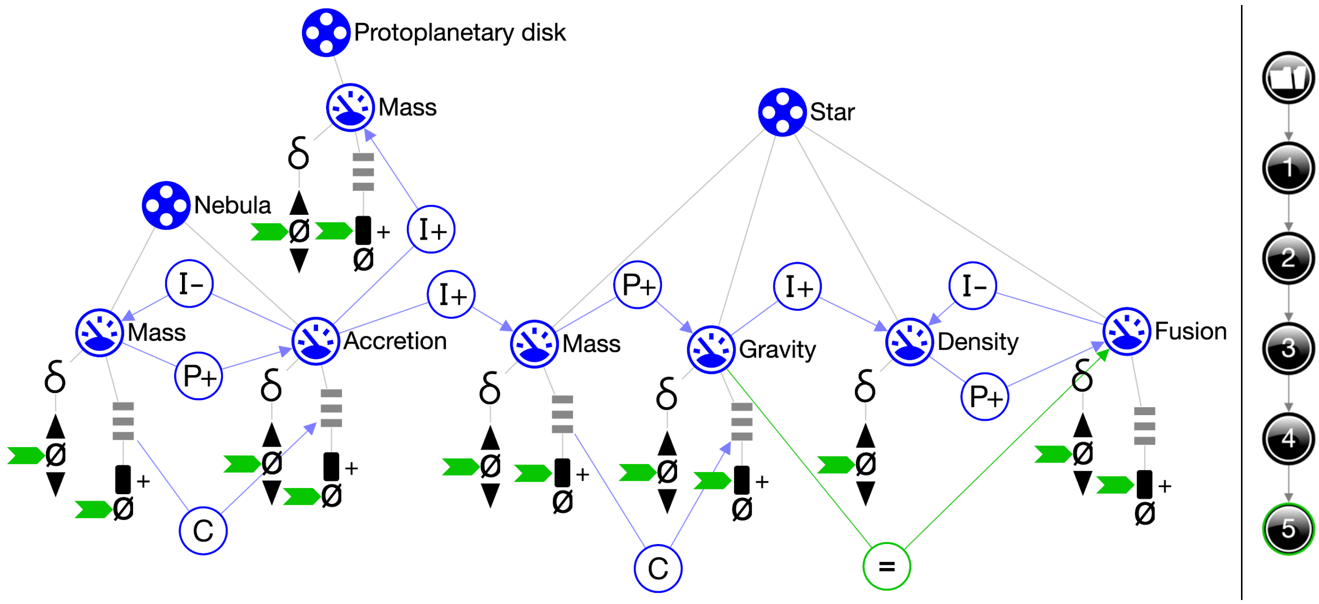

Figure 6. The simulation results for state 5 of the *fusion-gravity balance* model.

To support learners in developing this model, the workbook uses 6 steps. Each construction step is interleaved with simulation activities.

Learners built the full model from scratch and start by adding the Star with its Mass and Gravity, including the quantity spaces, the causal dependency, and the correspondence. Simulations are performed to ensure proper working of this first part. The second step focusses on Density being caused by Gravity and the fact that this is a process (steady gravity causing density to increase). Step 3 focusses on Accretion, but first only on the impact it has on the Mass of the Star. Note that, accretion is also a process. Step 4 includes the Mass of the Nebula and its relationship with Accretion. Step 5 focusses on Fusion and how it counteracts Gravity. Finally, step 6 adds the details regarding the Protoplanetary disk.

In addition to instructing learners in building the model and having them answer questions regarding the mechanisms, the workbook also presents notions of caution and the fact that a model is a simplification. E.g., it explains that the assumption that the mass of the star is zero is not entirely correct. That in fact, the star forms in the nebula. Hence, the moment the collapse of the nebula starts (i.e., accretion starts), the star already contains some material. For simplicity, however, the model assumes that the nebula and the star are separate from each other, so that the mass of the nebula flows into an 'empty' star.

7 Working with experts

Astrophysics experts contributed to creating the models presented in this paper. During each meeting improved versions of the model were presented to the experts for critical reflection. After consensus was reached with the first group, the model was reviewed by two further experts, in three consecutive sessions.

Most of the work focussed on the *star properties* model. In addition to clarifying terms and agreeing on the basic mechanism, most discussion concerned the notion of temperature and pressure before and after the start of nuclear fusion. Two postulates were formulated to reach consensus. Firstly, the model represents a family of stars, those in the *main sequence*, and not the specific behaviour of a single star. Hence, 'changing the mass of a star' (in the *star properties* and *star states* model) refers to comparing stars of different mass in the main sequence. Secondly, the quantities may refer to features at different moments during the lifespan of stars. As such, Pressure and Temperature (of the Core) refer to the features that led to the nuclear fusion starting, while Temperature and Gas pressure (of the Surface) refer to features that result from the nuclear fusion being active.

8 Classroom evolution

Evaluation of the lessons have been carried out (cf. [20]). Specifically, the *star properties* lesson has been evaluated in real classroom settings, the *star states* and *fusion-gravity balance* lessons have been pilot-tested with master students and reviewed by teachers.

Pilot. A pilot version of the three lesson activities were tested with three astrophysics master students, taking about 1 hour to complete a lesson. Students reflected on the activity and suggested improvements to the workbooks. The models remained unchanged.

Teachers. During a 90-minute teacher-training, physics teachers from the participating schools where informed about the three lesson activities and the evaluation study. Teachers agreed to reserve 90 minutes for *star properties* lesson, including a pre- and post-test.

Learners. One hundred and fifty-two learners from 9 classes from three secondary schools (across the Netherlands) participated in an evaluation study of the *star properties* lesson. Learners had no previous experience with learning by constructing qualitative representations. Results obtained during these lessons show that there is a significant positive effect of conceptual modelling on learners' understanding of the causal relationships between quantities of stars in the main sequence and the qualitative vocabulary [20].

9 Conclusion and Discussion

Three models and corresponding lessons have been developed to extend the Stargazing Live! mobile planetarium experience with lesson activities that relate to the Dutch secondary school physics curriculum. The lessons are available and can be taken online via https://dynalearn.eu/.

The *star properties* lesson focuses on learners identifying the key quantities that characterize stars and establishing the causal dependencies between those quantities. The *star states* activity follows on from the star properties lesson by adding ranges of qualitative values to six key quantities. During this lesson, learners learn how stars can be classified according to mass and how that relates to characteristic values for other quantities. The *fusion-gravity balance* model focusses on the birth of stars and how a balance emerges between the gravitational force (inwards) and the nuclear fusion force (outwards).

The lessons have been well-received by astrophysics master students and physics teachers in secondary education. The *star properties* lesson has been successfully evaluated in real classes in secondary education.

As future research we plan to evaluate the lessons on *star states* and on *fusion-gravity* balance. Furthermore, we intend to expand the set of conceptual modelling lessons to include other phenomena discussed in the planetarium lesson. For instance, we are currently developing conceptual modeling lessons related to circular and elliptical orbits of celestial bodies.

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