Summary of the PhD thesis

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Degenerate Objects.

Electron Degeneracy of Brown Dwarfs Interiors Expressed in Chemo-Degenerate Printing. Results of the Influence of Scientific Knowledge on Artistic Creation.

Intro

In my thesis I focused on the link between the results of the creation process of an artwork and a scientific discovery or theory (degenerate electron gas inside brown dwarfs), in the very specific context of this project. It became important to me to point the differences and similarities between Science and Art, when it comes to their outcomes. In my opinion, it is significant to notice how both are similar when one tries to comprehend or experience them, yet how much they differ when we think of their purpose. I also believe detailed consideration should be given to what we can learn about physical reality and our perception of its various manifestations through such diverse and yet comparable fields of human culture as Science and Art. It is essential for me, while working on science-art projects, to think about how the human mind and thought relates to the physical world. I based my considerations on this subject on Karl Popper's (1994) theory on body-mind problem and his idea of three worlds (the worlds of physical beings, of mental states and of theories and ideas).

For me as an artist the relation of Science and Art goes beyond inspiration and illustration. I call my artworks based on the scientific domain *expressions*. I understand such works as objects that show chosen aspects of our physical understanding of a certain phenomenon using a visual metaphor. Materials, media and the way the artworks are presented are all strictly connected to theories, experiments, and discoveries related to a chosen scientific problem. In the thesis I describe the physical properties of matter which was my first inspiration, and which became the topic and essence of the art series dedicated to them. I also show how and why the artworks got their final form, which is inseparably connected with both certain quantum properties of substellar matter and on the philosophy I chose as a base for my thinking on science, art and their relation.

Chapter 1

In the first chapter I focus on definitions and problems that they sometimes cause. Initially I explain the evolution of gas clouds that become stars and later gas disks around stars where planets are formed. I also try to describe brown dwarfs in relation to both planets and stars. I show why and how defining things might be tricky in certain science domains. While describing what stars are I take the opportunity to show why they cannot fail. Brown Dwarfs (BDs) are often referred to in popular science articles as "failed stars". As much as the idea of showing an object's nature in its name to simplify its further description is usually helpful, in this instance the proposed term is highly unsuitable. Only sentient beings are capable of failing, beings that *make plans* and can *expect* certain *results*. If they are not able to obtain these results, they *think* of it as a failure. Stars cannot fail, nor can any other physical phenomenon. We could name all stars "failed brown dwarfs" if we wanted to follow this logic. I would rather use the term "substellar object" in state of the term "brown dwarf" rather than the more common-sounding term "failed star". BDs are not "worse" kinds of stars, nor are they "better" kinds of planets. They are transition objects sharing properties of both planets and stars. BDs are at the same time different from both types of bodies. They are unique in their nature and that uniqueness is not assigned with superiority nor inferiority to other categories of objects. I use this example to point out that it is sometimes better to avoid very strict definition in order to conduct successful research as well as fruitful discussion with another person.

I also point out that it is important to remember that a definition can be helpful, and sometimes it is crucial. Within the quantum domain, for instance, only strict language of mathematics referring to very precisely defined phenomena can make further research and theoretical development possible. I do not discard definitions in general. My aim is to point that there are *specific* situations where it is not the best way to approach the process of describing nature.

Some features of the art series in relation to the scientific topic are also presented in Chapter 1. For instance, the mass boundary of 13 Jupiter masses in which deuterium fusion can start for a small period of time (and which can be seen as a minimum BD mass) was an important value to determine the number of artworks that are part of this project. The whole series consists of 13 objects within which different expressions of electron degenerate matter inside BDs are placed.

I wanted to build three-dimensional images that would be the expression of the degenerate matter that BDs are made of. Therefore, the concepts of gravitational collapse of gas cloud regions that give birth to stars and brown dwarfs, and that of planets forming from the gas disks surrounding young stars and brown dwarfs, were an important factor for me in choosing a way to build my

images. Since brown dwarfs share many qualities with both stars and planets, the process of formation of stellar and planetary objects, as well as BDs, was interesting and important for me in the process of creating the art series for this project.

I further describe the process in question, which was started with scans of the air in my studio. By this I mean the simplest, most non-scientific method that came to my mind - were just scans of space of the room when the scanner was opened and nothing was placed on its glass. I initially needed dark images to work on and I decided that some even very loose connection to a picture of gas would be relevant in this situation. As contracting gas in outer space gives birth to stars and brown dwarfs, I also worked on gas in the form of an image, which visual quality was later altered by applying the strong, physical pressure of a printing press, through which all the printed scans have passed. To make them "degenerate" (different from the original, "normal" gas that they were representing) I used various chemical reagents that changed the initial images combined with the pressure of the printing press.

The process is then described in more detail. After obtaining a number of prints I intuitively chose thirteen that were in my opinion the best representations of my knowledge of degenerate matter and the formation and evolution of brown dwarfs. These prints were then scanned and thoroughly digitized. Each image was split into multiple layers (around ten) and then printed and applied on various transparent and semi-transparent materials to create the final three dimensional image.

Because the process of formation of stellar and substellar objects is complicated and depends on many factors, each work at this stage was different and the results were more often than not completely random. I chose a group of works that exhibited qualities I decided were relevant.

Then I amplify the domain of small things - in this chapter small in astronomical standards (small domain in the meaning of particles and quantum effects is carried out in Chapter 3). Not only substellar small bodies are presented in this chapter, but also the importance of scale in general is put into focus.

Chapter 2

In Chapter 2 insides and insights are discussed. I present some theories about looking at reality from a scientific point of view as well as theories and research concerning the interior of brown dwarfs and basic physical properties of stellar, substellar and planetary matter.

I present insights of chosen philosophers of science into our understanding of physical reality. I start with the Theory of Everything (attempts to merge the Theory of Relativity and Quantum Theory) and further focus on Bohm's and Heisenberg's insights into theory that would allow to describe more than relativity and quantum mechanics can.

I describe Bohm's (2008) way of thinking on nature of theories and therefore on understanding reality. It had a great impact not only on my thinking about science but also on the main method applied to create the artworks in this project. Bohm's hologram was a reason for me to metaphorically refer to this form of looking at the world. I decided to create three dimensional images that would refer to the form of a hologram - a three dimensional projection of the whole, undivided reality that allows to see many aspects of it at the same time. An actual hologram was not used because the method I chose had other important qualities that mirrored some of physical and philosophical aspects referred to in this text. The fact that many physically applied layers build the images is a metaphor of different variations of undivided wholeness that together are inseparable and when looked upon as a whole, show a totality. But this totality cannot be grasped nor measured, and this feature of Bohm's reasoning is well expressed in the fact that the artworks created in this project cannot be reproduced nor documented in a satisfactory way.

Each image is not only spatial, it also fluctuates, which makes its satisfactory documentation nearly impossible. Fluctuations of the image depend on the angle from which it is observed and even small movements of the viewers head induce changes in the image that can be seen, and the final visualization of it is impossible to show nor grasp. This feature is also a mirrored metaphor of the fact that we cannot obtain nor interact with degenerate electron gas in hydrogen here on Earth. It is possible to study it only through theoretical calculations and indirect observations of very distant (and faint) objects placed many (sometimes even hundreds) light years away from Earth. Even Jupiter, which is fairly close to Earth, is possible to investigate only through satellites (like Juno, which orbits Jupiter and sends lots of valuable data since 2011). That makes the study of the planet's interior only an indirect process. As metallic hydrogen can only be interacted with indirectly, my art series about this kind of matter are, in contrast, possible to be fully grasped *only* in direct contact with the artworks.

Further I show that brown dwarfs are sometimes referred to as "failed stars" because they "fail" to sustain nuclear fusion on p-p chain. Their mass is not high enough for the gas in the object's center to reach temperatures allowing it to ignite and sustain nuclear fusion. However, nuclear fusion of deuterium is sustained for a brief period of the BD's life (sometimes even hydrogen fusion in case of high mass BDs) but soon primordial deuterium is depleted and further nuclear

reactions are stopped by growing degeneracy of the object which makes it cool faster. As a result of this process gas contracts further, since nuclear reactions are no longer present to prevent its contraction. Gravity is stopped at a certain point, preventing a BD from further collapse under its own weight by the so-called Pauli Exclusion Principle. It states that two fermions (in this case electrons) in the same quantum system cannot have the same quantum state. Electrons prevent further contraction, which is why that kind of degeneracy is called electron degenerate matter.

Chapter 3

In Chapter 3 I attempt a more detailed and quantum effects-oriented deliberation on the interiors of BDs - electron degenerate matter. When talking about the quantum domain, we cannot take into consideration states or phenomena we are familiar with in the large-scale world that we are used to encounter in everyday life. The model of an atom resembling a small solar system with a nucleus as the Sun and electrons as planets orbiting it has long been considered unsuitable, as are illustrations of molecules widely used in chemistry handbooks showing all particles as small balls connected with small sticks that symbolize chemical bonds. In reality (as much as we can talk about the reality in the quantum domain), the world of particles is described by probability functions. An electron, for instance, is not a being like we are used to describe - it is a probability of a set of properties we call an electron, happening in an area described by its probability function. It is something between a particle and a wave, exhibiting properties of both but being neither at the same time. Electrons are not "orbiting" atomic nuclei. They manifest certain qualities we learn that electrons exhibit with given probability in different places around the atomic nucleus. As the theoretical chemist, professor Piotr Petelenz, put it during his guest lecture on quantum mechanics in Academy of Fine Arts in Krakow in 2015, we can call it *sculpting in the fog*.

First, I point different approaches to quantum mechanics in general by selected scientists and philosophers researching this area of physics. Bohm (2008) suggests that we should implement a new form of language in order to talk about new order in Physics, that in his opinion quantum theory is an entry for. I describe his experiment on the form of language that would be suitable for talking about quantum theory and its further development (holomovement) that he calls the *rheomode*. He analyses words and their meanings, etymology etc., and tries to formulate sentences in a manner that would allow our thinking not to be focused on fragmentation of the world anymore. Bohm underlines that our worldview is deeply rooted in language. The structure of language helps or prevents us from seeing certain aspects of the world. Since all entities of world 3 described by Popper (1994) are formulated in a language and language is a tool that allows us

to enter world 3, this topic is very important when talking about the formulation of the laws of Physics in words, without mathematical schema. Bohm states that the pure fact of bringing this problem to our attention, as well as the contemplation of the structure of the language and its consequences on our perception of the world is a step further into changing the perspective that prevented us from grasping ideas from a different point of view. He suggests that the fragmentary aspect of our language, and therefore our thinking, prevents us from seeing the world as an undivided wholeness and formulating physical laws this way instead of the way we did so far. Heisenberg's (2007) point of view on language is very similar. Even though he did not suggest any specific way to change the way we formulate words or sentences, he brought to attention the fact that our use of language does not suit physical laws of particles anymore. But he also stated that pure awareness of this fact and therefore use of language while keeping in mind that it is only conventional makes us think differently and therefore allows us to be a little bit closer to the truth.

Then the term "degeneracy" is described in the context of its usage in science. It has various meanings - in Mathematics, Biology, Chemistry, Physics and Astrophysics. Those meanings are different from the common understanding of the word (which is associated with decay). To make things more clear I describe the most essential meaning that is helpful to better grasp the nature of degeneracy that is the topic of this project. I also discuss other meanings that are familiar with it and are helpful in grasping a context in which I call something "degenerate" (either matter or art works that are part of this project).

Then I describe certain phenomena and effects taking place in electron degenerate matter. The point is that in a classical gas, to which the Exclusion Principle does not apply, there is no bound on the number of particles occupying the same state: the particles do not obstruct each other's response to the energy supplied by the surroundings. Accordingly, their majority have their energies on the order of the (average) amount kT maintained by the thermostat. In Fermi gas, on the contrary, only one particle per state is permitted, so that the occupied states spread up to the incomparably higher energy $E_{F,}$ which leads to a much higher total energy of the gas, and consequently to its enormously *increased pressure*.

At very high temperatures, the properties of the Fermi gas approach those of a classical gas ("weak degeneracy"). In such conditions, the Fermi gas behaves like a classical one (it becomes "nondegenerate"). This is what happens in stars, which are very hot due to ongoing nuclear fusion inside them. In this comparison, the manifestations of Fermi gas strong degeneracy are indeed spectacular, just as the term suggests. Moreover, degeneracy of hydrogen is something very exotic for us, since it was not yet encountered in any Earth laboratory[1]. This unusual kind of degeneracy is crucial for brown dwarf physics, differentiating BDsfrom stars and most of the planets.

I point out that degeneracy of electron gas is something happening commonly around us. It is a feature of electrons in any metal (in the chemical, not the astrophysical meaning of the word) at low, room temperature. What makes degenerate matter different from anything we know from everyday encounters or laboratories on Earth is that in brown dwarfs *hydrogen* displays these qualities and obtains metallic properties responsible for the degeneration of electron gas (hence the name for electron degenerate matter - metallic hydrogen).

Different meanings of the word "degenerate" are also presented and briefly described, since the word has entirely different meanings in scientific and common language. The first association one might make when thinking on the origins of our contemporary understanding of "degeneracy" in a social context might be misleading and simplified. Nazis were not the only ones in their time that used the word nor was their interpretation of it the most popular one.

I describe how Pick (1989) presents consequences and historical apprehension present in Italy, England and France at the turn of the nineteenth and twentieth centuries. His study shows that degeneration cannot be reduced to a simple model of manipulation or ideological crusade. It was a term widely used in many contexts, "chosen freely at will by various professional groups" (p. 234). He gives examples of philosophers (Nietzsche, Foucault), doctors (Freud, Morel, Lombroso, Maudsley) or novelists (Zola, Buchez, Taine, Le Bon), among others.

The title of this project is "Degenerate Objects". It refers not only to brown dwarfs that contain degenerate electron gas, but also to the products of my search for imagery as an artist. When addressing the art series that is part of this project and using the word "degenerate", I do not mean it in the sense that has its roots in the nineteenth century and is associated with decay and developing negative qualities. For my own purposes I use the word only in connection with physical degeneracy as described in Chapter 3. The artworks that are the result of this knowledge are inseparably bound with it. I categorized the project as science-art because the artworks are deeply rooted with chosen research on physical phenomena and are meant to go beyond illustration. In this context they are called "degenerate" because process of their creation metaphorically refers to processes taking place inside BDs. They are also degenerate in the meaning of pushing matter to its physical limits - as I did with air scans prints while changing them with strong chemical reagents under significant printing press pressure. It is important to stress out that both scans of the air and pressure applied to them via printing press are only metaphorically referring to physical changes of hydrogen gas under significant pressure.

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1 Eremets and Troyan (2011) claimed they obtained a metallic hydrogen in their lab, but the experiment was widely criticized later. The article by Amato (2012) points out that it is nearly impossible, as suggested by the fact that the results were not reproducible. In the article he analyzes why the scientific community is skeptical about this claim.

The context of the Latin root of the word “degenerate” is important for me when referring to this art series. As described earlier, it translates to “no longer of its kind”, meaning anomaly. The works are meant to be something hard to define and impossible to document in a satisfactory way. They are bound with very precise topic and physical knowledge that go beyond emotional inspiration over the Cosmos. Their form is also meant to refer to the quantum domain, which is not intuitive nor possible to grasp fully with our human minds, since visualization of it is not possible and our language lacks a good form to describe its properties satisfactorily. When attempting to create an imagery that refers to physical domain that cannot be seen nor described without equations, any possibility for artworks to become simple illustrations of physical processes is, in my opinion, prevented by the mere nature of the processes in question. And the best metaphor of our inability of developing imagery or non-mathematical language that would be suitable for quantum phenomena was for me the fact that the artworks, the three dimensional prints, are impossible to be reproduced successfully in a photo or a video. Furthermore, the weird features of quantum mechanics are metaphorically referred to in the form of the boxes inside which the three dimensional images are placed.

Some aspects of the series are further described. All thirteen objects are cubes of the same size, identical in shape. They are not only simple, minimalistic frames for the images inside them - they are also meant to represent our mathematical language of the quantum domain where it is convenient to visualize free particles as contained in a very large “box”. In quantum description, symmetry of the container inevitably leads to degeneracy of the energy levels. In the quantum world, the higher the symmetry, the higher the degeneracy The exterior form of the objects in the series is meant to refer to that particular aspect.

Not only is the shape of the boxes significant in relation to the quantum properties of metallic hydrogen, but the metal they are covered with represents the electron gas, which in these conditions is certainly degenerate. Then, the exterior of each work allows one to touch a surface that contains the degenerate electron gas, and the insides of the boxes abstractly allude to metallic hydrogen that BDs are made of.

Summary

As Dawkins (1998) describes, pure scientific knowledge can be a beautiful and intriguing area of human culture that might be -and sometimes is- an inspiration or a topic for works of poets or artists. Just as Feynman (1964) said, knowing more about something mysterious does not take away its beauty. Scientific knowledge should be a delight for our minds and since popularization

of scientific research is vast and growing, it is not that hard to dive into any topic that seems to be intriguing. As any area of human culture, activity or interest, science can be a reason and theme for artistic creation or for a research for new imagery in visual arts. For me, as an artist, knowing more about our forms of insight into the physical world creates a possibility for developing different ways of visual creation. This project is an example of such an approach.

As described earlier, I had some assumptions towards the art series that were based on knowledge about degenerate electron gas within brown dwarfs. However, as is the case in any creative work, some of the conclusions came to me only after the creation process of the images began and I could relate the first presumptions to the actual outcomes.

I describe that, for instance, the idea of creating symmetrical boxes for the works, as well as covering them with a metal layer to add actual degenerate electrons to the series came to me already while working on the images and discussing quantum subtleties with professor Piotr Petelenz. The many layers that each image is made of showed themselves to me as yet another metaphor, apart from the one that made me choose this kind of spatial imagery, which relates to the form of hologram. I saw many layers pressed together not only as abstractions of the whole that together make totality, but also as a representation of the changing properties of hydrogen gas under growing pressure. Also, the images themselves are mostly *expressions* of the evolution and changing of properties of hydrogen with growing pressure and electron degeneracy. They do not allude only to the properties of metallic hydrogen as it is (meaning fully degenerate electron gas).

While working on the artworks I also came to the conclusion that many layered images allude to Bohm's hologram in more ways than only their spatial properties and parts abstracted from the totality in form of each of the layers they are made of. Each layer can be seen as an abstraction of the whole - not only metaphorically, but as an abstraction from a particular image. Pressed together they form flowing, three dimensional images, changing at all times while being observed, making it possible to see different references to metallic hydrogen and its origins. These analogue holographic images are not only an analogy to Bohm's theorem on looking on the physical world, they are examples of that kind of observation, giving an opportunity to look at an image differently.

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