Exoplanets in physics classes

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Abstract. The opportunity to use a new scientific discovery in physics lessons is presented in order to illustrate how they can be interpreted in the course of public education. Students were asked to estimate the mass of a red dwarf star using the data regarding its planets published in a news article, and through the use of the learned laws of physics. The aim was to develop the students' knowledge of mechanics, to expand the elements of the Newtonian approach, to deepen their astronomical knowledge and to practice research methods. This new approach was tested in two classes, and the results were the basis of the thesis of a graduate teacher. The problem was also solved by 70 college freshmen as a test of their physics skills acquired in general education.

1. Introduction
It is important in the course of science education to show the way in which scientists approach a problem, how to begin investigating, how to formulate a question, what simplification conditions to introduce. An important task of the teacher is to develop a realistic picture of science and research, and to show that science is an ever-changing system. An excellent opportunity for this is the research-based processing of new scientific discoveries. The critical thinking of the students can be enhanced by analysing news published on the Internet in a curriculum at school.

In this paper an example is shown how the discovery of a new nearby star system was introduced in the classroom. The theoretical framework for this analysis is Kepler’s 3rd Law and Newton’s 2nd Law taught in mechanics. Depicting the data and performing the calculations develops the proportionality thinking of the students. It is important to use Microsoft Excel or similar programs, use functions and parameter for the calculation, where special attention should be paid to the units of the measured data.

Research procedures were used to analyse the news article. How did the researchers get to the new discovery? What hypotheses did they have that motivated the targeted observations? How, when, where and what kind of observations were made? How have the collected data been analysed?

This new approach was tested in two classes in school by a graduate college student of physics education. The problem was also solved by 70 college freshmen to test their skills in physics.

2. The course of the lesson in class
Below is a description of possible processing steps for the topic, which was actually implemented in a school environment, in two 9th grade classes. The processing was carried out on the recommendation of the author by a graduate college student of physics education. The study detailed below formed the basis of the dissertation of this college student [1]. The basic steps of processing the topic were:

1 This study was supported by the Content Pedagogy Research Program of the Hungarian Academy of Sciences.
Introducing the topic
- Analysing the text of the online news article through questions
- Calculating the mass of the red dwarf in three different ways
- Calculating the mass of Jupiter from the data of its moons as a homework
- Watching, analysing, and comparing similar news reports on exoplanets

The students had to read the Internet article at home, and then answered the questions individually during the lesson at school, which was then discussed together. The text has been slightly modified for the students [1] [2] [3] [4]. The teacher asked questions during the lesson about the topic to guide the students. The following questions were asked about the article:

1. What did the researchers discover?
2. Where is the telescope with which the discovery was made?
3. Where were the researchers?
4. What methodology did the researchers use?
5.a What kind of celestial body was investigated?
5.b How far is it from us?
6. Why did the researchers continue to explore and what tools did they use?
7. What further research is planned and what will they use?
8.a How long have we known about exoplanets?
8.b How many exoplanets were discovered?
9. What types of exoplanets have been first discovered and why?

2.1. The seven dwarfs and the red dwarf

The following text is a translation of the Hungarian article published on the Internet, that was given to the students. The text was slightly modified for students to ease its understanding [2]. The numbers in parentheses in the text refer to the corresponding questions listed above (not part of the original text).

“For the first time in the TRAPPIST-1 system, planets were discovered in 2015 by the Belgian-developed astronomers looking at TRAPPIST telescope (2) in Chile. As its name suggests, it was the first planetary system discovered by experts with a (3) Liege-controlled robotic telescope. The first three planets were announced in 2016. They were discovered by this method of coverage, that is, the brightness of the star was measured and it (1) was investigated whether there were periodic fads that could be caused by planets circulating around it at regular intervals.

This sounds very simple in theory, but in reality it is much more complicated. On the one hand, very small changes in light have to be noticed, as the largest planets are not able to blur the relative brightness of their stars by more than 1 percent. On the other hand, not only planets can cause temporary fading, but also a number of other factors, such as the star’s own activity cycle. Thirdly, the identification of periodic fads becomes very complicated if they are not caused by one planet, but by two or more (Figure 1).

The combination of these factors leads to the fact that the extrasolar planet discovered by the most overlapping method is a so-called (9) hot jupiter, that is, a planet that is relatively large in size compared to its star and is very close to the central body, so it often crosses over so it can be noticed in a short time.
For TRAPPIST-1, it was fortunate for experts to have a very small and cold star in the center of the system. The celestial body is a M8-(5a) class red dwarf, meaning that its mass is only 8 percent of the mass of the our Sun, and its radiation is two thousandth of our stars. Thus, TRAPPIST-1 is hardly larger than Jupiter and has a surface temperature of about 2550 K, compared to 5778 K of the Sun.

If an earth-like planet crosses a star like a Sun, it reduces its brightness by 0.1 percent. However, if the same planet passes before TRAPPIST-1, it will cover 1 percent of the starlight. Such a fluctuation is much easier to detect, even if the star is very faint. In addition, for TRAPPIST-1, it has also contributed to the success of us by being very close to it on the astronomical scale: it is only (5b) 40 light-years away from us in the Aquarius constellation.

As it turned out above, (4) the magnitude of the fluctuation of the brightness, given the size of the star, can be determined by the size of the migrating planets. Based on this, the first three discovered planets of TRAPPIST-1 seemed to be the same size as Earth, but the astronomers at the same time noticed that something was not quite right in the system. The transitions did not follow each other properly, but they always differed slightly from what was expected. (6) And that meant that there could be other planets around the star whose gravity influenced the passage of known celestial bodies, slightly altering their orbital periods.

When it became clear, (7) the experts immediately began to search for new planets (this time with the help of more sensitive binoculars, Spitzer and VLT), and soon they came across four other planets. So around the TRAPPIST-1 there are a total of seven planets circulating (at least we know so much at present), all of which are roughly similar in size to Earth. The smallest (TRAPPIST-1h, or outermost body) diameter is about 75 percent on our planet, the largest (TRAPPIST-1g, the previous inner neighbor) has a 1.27-times diameter. As far as the masses are concerned, the latest available data suggest that the third planet (TRAPPIST-1d) appears to be 0.41 times the earth's mass, and the largest is its inner neighbor (TRAPPIST-1c), which is 1.38 times like our own planet.

The brightness measurements reveal another important data, since the length of time a planet has to pass can be used to infer the length of its circulatory time. This also shows how far they are from the...
star, because the more distant planets are slower. As for the TRAPPIST-1 system, all seven known planets are closer to their stars than Mercury to our Sun. The innermost celestial body circulates in its orbit for only one and a half days, and the outermost for 14-25 days (Figure 2).

![Figure 2. The data of the planets [3]](image)

However, despite their proximity to the star, the planets are not as hot as Mercury, as the star emits much less energy than the Sun. In fact, the surface can be quite pleasant on the surface. Although it is difficult to judge the actual circumstances without knowing the atmospheric conditions and there are disputes about the criteria of potential life, computer models suggest that at least three planets (TRAPPIST-1e, f and g) are at a sufficient distance from the star so that liquid water may exist on their surface.

If someone stood on the surface of one of the planets, he would probably encounter very pale light: it would be a little brighter than a full moon night. At the same time, the central star would look much larger than the Sun on Earth, says Amaury H. M. Triaud, a member of the discovery research group. For example, on TRAPPIST-1f the star's disk seems to be three times as wide as the Sun on our planet. The color of the star seems to be the same for all experts. Since it emits a large part of its energy in the infrared range, for the human eye (not accounting for the composition of the planet's atmosphere), we would probably see everything in the shades of orange red.

Whether we could exist on these planets, however, is a question that we have no answer at the moment. As mass of planets is concerned, only very rough estimates are available for the time being, on the basis of how they “pull” each other as they move around in their orbits. In the absence of accurate data, it is difficult to judge the density and composition of the planets, and whether they have an atmosphere at all. That is, at the moment we have no idea how earth-like these planets are. In fact, these are roughly as large as our own planet, but we do not know what their surface is like, and whether they have an atmosphere, which is an important factor in judging living.

However, the news of the discovery is still very exciting. On the one hand, because 40 light years really is just a spit in cosmic distances. Though it is far beyond the current technology to travel, proximity means that more new telescopes that will be deployed in the coming years will discover even more details about the planets of TRAPPIST-1. For example, with the James Webb Space Telescope, even the individual planets could be directly observed, so it will soon be possible to determine whether they have an atmosphere and, if so, what it’s made of. And if the new instruments could detect oxygen, methane, ozone and carbon dioxide in the atmosphere of a planet and possibly determine a certain proportion of them, we could say with 99 percent confidence if there is life on that planet, says Michael Gillon, head of the research team.

Another thing that makes the detection of the planets of TRAPPIST-1 a very important milestone is the number of planets discovered so far. The first planet outside the Solar System was discovered by astronomers in 1988, and the first enhanced detection took place in 1992 (Ba). That is, thirty years ago we knew about the existence of a total of 9 planets (then even Pluto was in this category). In the nineties, astronomers found more and more exoplanets. In 1995, the discovery of the first planet circulating around a Sun-like star, but only in 2015 was the first celestial body of a size similar to Earth (i.e. a good chance of a rocky planet) discovered, that is circulating in its viable zone.
At present, there are (8b) a total of 3457 known exoplanets in 2625 systems. What immediately shows one of the most important recognitions of the past decades is that the number of planets in the universe is likely to exceed the number of stars. Not all stars have their own planets, of course, but there are a number of stars with several attendants, like the Solar System or TRAPPIST-1.

Starting from the available data, there are many planets in our galaxy and other star systems, including many earth-like bodies. When the exoplanet discoveries began, the experts used to find only hot jupiters for a long time, which was surprising for astronomers because this type of body does not exist in our solar system. However, as detection technology evolves, more and more smaller planets are discovered. For example, around the TRAPPIST-1 it was possible to detect seven of them, which was never the case before. And however we look at it, the likelihood of finding life in the universe similar to life on Earth has grown significantly, statistically speaking.”

3. The problem
In school classes, the processing of the text was followed by the estimation of the mass of the dwarf star using the data contained in the article. It was done in joint class work, under the guidance of the teacher.

Seven small, Earth-sized planets circulate around a so-called dwarf star named TRAPPIST-1, about 39 light years from us, so relatively close by. It was announced by researchers at NASA in a press conference on 22th February 2017. The circulation period and the average distance of the planets from their star is given in the table below, and it is also depicted in a graph.

- Use the data and the graph (Figure 3) to estimate the mass of the dwarf star!
- Compare the mass of this star with the mass of the Sun!
- What approximations and assumptions were used in the estimation?

One Astronomical Unit is the Sun-Earth distance of $1.5\times10^{11}$ m, the gravity constant is $\gamma = 6.67\times10^{-11}$ Nm$^2$/kg$^2$, the mass of the Sun is $2\times10^{30}$ kg.

![Orbital data of the planets](image)

**Figure 3.** The orbital data of the planets. (Author’s own figure.)

Calculations using the data of planets or moons is a part of the compulsory curriculum, so it can be solved as a regular task in class. For the graph method, it is an important element to discover Kepler’s Third Law in the equation of the fitted curve (the exponent being 1.5).

4. The foundations of the solution
Newton’s law of gravitation is applied to the planetary system, where $M$ is the mass of the star, and $m$ is the mass of one planet. The orbit of the planet is approximated to be circular, the effects of the planets on each other is ignored. The motion equation is:

$$\frac{\gamma M m}{R^2} = m \cdot R \cdot \omega^2$$  \hspace{1cm} \text{where} \hspace{1cm} \omega = \frac{2\pi}{T} \hspace{1cm} (1)$$

$$\frac{\gamma M m}{R^2} = m \cdot R \cdot \frac{4\pi^2}{T^2}$$  \hspace{1cm} (2)
hence we can simplify with the mass of the planet \( m \)

\[
\frac{\gamma M}{4 \pi^2} = \frac{R^3}{T^2}
\]  

(3)

which is actually Kepler's Third Law, which we can rearrange to the following form for further calculations:

\[
T^2 = \frac{4 \pi^2 R^3}{\gamma M}
\]

(4)

Three methods of solving the problem

1. Calculations using the data of each planet using the equation above.
2. Using Excel or other spreadsheet software, applying computer skills.
3. In the graph method it is an important element to discover Kepler’s Third Law in the equation of the curve.

4.1. Calculated from the graph

The equation of the power function curve fitted in Excel:

\[
y = 1345.2 \cdot x^{1.5062}
\]

(5)

The exponent of \( x \) is approximately 1.5. Raising the equation square:

\[
y^2 = 1.81 \cdot 10^6 \cdot x^3
\]

(6)

in which Kepler's 3rd law can be discovered.

Note that in the data in the table and on the curve is in days, which is \( 8.64 \cdot 10^4 \) s, and the distance is in Astronomical Units, which is the Sun - Earth distance of \( 1.5 \cdot 10^{11} \) m, as given!

Because of the units of measurement, we need to transform Kepler's 3rd Law:

\[
T^2 \cdot (8.64 \cdot 10^4)^2 = \frac{4 \pi^2 (1.5 \cdot 10^{11})^3}{\gamma M (8.64 \cdot 10^4)^2} R^3
\]

(7)

and it can be seen that the fitted curve’s parameter hides the weight of the dwarf star.

\[
\frac{4 \pi^2 (1.5 \cdot 10^{11})^3}{\gamma M (8.64 \cdot 10^4)^2} = 1.81 \cdot 10^6
\]

(8)

The gravitational constant \( \gamma = 6.67 \cdot 10^{-11} \text{ Nm}^2/\text{kg}^2 \)

or fully with base SI units \( \gamma = 6.67 \cdot 10^{-11} \text{ m}^3\text{kg}^{-1} \text{s}^{-2} \)

Since the gravitational constant is known, only the mass of the star \( M \) in the equation is unknown.

\[
4 \cdot \pi^2 \cdot 1.5^3 \cdot 10^{33} = \gamma \cdot M \cdot 8.64^2 \cdot 10^8 \cdot 1.81 \cdot 10^6
\]

(9)

\[
M = \frac{4 \cdot \pi^2 \cdot 1.5^3 \cdot 10^{33}}{6.67 \cdot 10^{-11} \cdot 8.64^2 \cdot 10^8 \cdot 1.81 \cdot 10^6} = \frac{135 \cdot 10^{33}}{901.2 \cdot 10^3}
\]

(10)

\( M \approx 1.5 \cdot 10^{29} \) kg, which is less than one tenth of the mass of the Sun, approx. 8% of it.

4.2. Calculated from the table

From the data pair of any planet, the circulation time and distance from the star gives the mass of the star, which can be calculated as

\[
T^2 = \frac{4 \pi^2 R^3}{\gamma M}
\]

(11)

Due to the units of measurement, it has to be slightly modified, as was the case with the graphical calculation.

\[
T^2 \cdot (8.64 \cdot 10^4)^2 = \frac{4 \pi^2}{\gamma M} \cdot (1.5 \cdot 10^{11})^3 R^3
\]

(12)
Arrange the relationship with the mass

\[ y \cdot M \cdot T^2 \cdot 8.64^2 \cdot 10^8 = 4 \cdot \pi^2 \cdot 1.5^3 \cdot 10^{33} \cdot R^3 \]

(13)

\[ M = \frac{4 \cdot \pi^2 \cdot 1.5^3 \cdot 10^{33}}{6.67 \cdot 10^{-11} \cdot 8.64^2 \cdot 10^8 \cdot T^2} \cdot R^3 = 135 \cdot 10^{33} \frac{R^3}{T^2} \]

(14)

\[ M = 0.27 \cdot 10^{36} \frac{R^3}{T^2} \]

(15)

The \( R^3/T^2 \) ratio for each planet is approximately: 5.78 \( 10^{-7} \)

\[ M = 0.27 \cdot 10^{36} \cdot 5.78 \cdot 10^{-7} = 1.56 \cdot 10^{29} \text{ kg}. \]

The assumption is that only the interaction between the planets and the central star was taken into account, but not the effect of the planets on each other. It is also important, as the planets are very close together in astronomical sense. We approached Kepler's third Law, taking the orbits as round. You can see from the function alignment that this is not fully compatible with the data.

4.3. The easiest method

The circulating time is converted to year, so you can count on units similar to Earth. The calculation can be easily done using Microsoft Excel of a similar spreadsheet program (Figure 4.).

| \( R^3/T^2 \) | \( R \text{ (AU)} \) | \( T \text{ (day)} \) | \( T \text{ (year)} \) |
|----------|------|-------|------|
| 0.0778   | 0.011| 1.51  | 0.00414 |
| 0.0768   | 0.015| 2.42  | 0.00663 |
| 0.0752   | 0.021| 4.05  | 0.01110 |
| 0.0786   | 0.028| 6.1   | 0.01671 |
| 0.0796   | 0.037| 9.21  | 0.02523 |
| 0.0796   | 0.045| 12.35 | 0.03384 |
| 0.0719   | 0.06 | 20    | 0.05479 |

Figure 4. The \( R^3/T^2 \) ratio for each planet.

The \( R^3/T^2 \) ratio provides a value relative to the Sun Mass, and this is actually just under 8 %. This is because the astronomical unit is the mean radius of Earth's orbital and the unit of circulatory time is 1 year, so the ratio for the Solar System is approximately 1.

With the three methods mentioned above, nearly identical results can be obtained for the mass of the dwarf star, since – in fact – the theoretical basis for all of them is Kepler's 3rd law.

5. Test results

In addition to the two 9th grade classes, where all three methods were used by the class together with the teacher (graduate student), the above task was solved by 70 first-year undergraduate physics students at the time of their admission. This task was part of a larger test, compiled and corrected by the author, and it was the most difficult part of it. The aim of this test was to classify them into learning groups based on their knowledge and skills. The third solution to the task, using Microsoft Excel, could only be discussed in the two 9th grade classes, as the university students wrote paper-pencil tests, so they did not have the opportunity to do so. They mostly resulted to the first method.

The average points received for this task was 4/10. Half of the students were placed in support groups to help fill their gaps in knowledge of high school physics. Relatively many were able to calculate the mass of the red dwarf star, even if they didn’t know what to do with the graph and the approximation question. 6 people got a maximum score, which is good for such an unusual and complicated task. These students were mostly winners of student competitions and they will receive a higher level of education right from the start of their university studies.
6. Conclusions
After processing, we talked to the high school students about the online informative article itself and the novel curriculum processing method. They said that they liked the article and the task based on it, especially the part where the Excel was used. They were happy to learn physics this way. Following the test at the university, the students also said that they liked the task due to the novelty of the task, and that the appearance of one of the latest discoveries in the test was unexpected and welcome.

In summary, it is definitely worthwhile to include the latest scientific contributions to knowledge in education, using the informative articles that report on it, and to link them to the compulsory curriculum. It also has motivational value in school and university as well. During our curriculum development work, we have prepared several novel tasks and work plans for teaching physics along with numerous methodological recommendations, giving special attention to the possibilities of the development of thinking. We have made suggestions to incorporate them into the educational process, supplemented by the experience of students and colleagues in public education. Several examples were developed in detail and these were collected into a book that is currently under publishing [5].

7. References
[1] Kindl E: Expolanets in physics classes, Dissertation, ELTE Department of Science (2018)
[2] https://m.ipon.hu/elemzesek/a-het-torpe-meg-a-voros-torpe/3101 Internet article, last download: 05.04.2020.
[3] Gillon M, Jehin E, Lederer S, Delrez L, de Wit J, Burdanov A, Van Grootel V, Burgasser A, Triaud A, Opitom C, Demory B, Sahu D, Bardalez Gagliuffi D, Magain P & Queloz D: Temperate Earth-sized planets transiting a nearby ultracool dwarf star https://www.eso.org/public/archives/releases/sciencepapers/eso1615/eso1615a.pdf
[4] Gillon M, Jehin E, Burdanov A, Delrez L, Fernandes C, Van Grootel V & Magain P: Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1, Nature, Volume 542, pages 456–460 (23 February 2017) https://www.nature.com/articles/nature21360
[5] Korom E., Radnóti K. (editors): A fizika tanulása és tanítása a gondolkodásfejlesztés tükrében, (Learning and teaching physics and developing student thinking.) MOZAIK Szeged (book under publishing, 2020)