ESA/ESO SciOps 2022: Artificial Intelligence for Science and Operations in Astronomy

Previously Undiscovered Exoplanets Detected with Deep Learning

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INTRODUCTION (1)

Background Information

★ The NASA Kepler space telescope observed 530,506 stars for 9.6 years to find potential exoplanets that may be orbiting them (https://exoplanets.nasa.gov/keplerscience/).

★ In the Kepler data, professional and citizen astronomers have discovered 2709 confirmed exoplanets and 2057 other exoplanets yet to be confirmed as of May 15, 2022 (https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html).

★ The Kepler mission collected a huge amount of data and posed a question for us: How can we efficiently detect objects of interest such as exoplanets in the huge data?

★ Pearson et al. (2017) reported that their convolutional neural network in DL was capable of detecting Earth-like exoplanets in noisy time series data with a greater accuracy than a least-squares method. Their study indicated that machine learning, and actually the DL they tested, would facilitate the characterization of exoplanets in future analysis of large astronomy data sets.

INTRODUCTION (2)

★ Zucker et al. (2018) examined the feasibility of using convolutional neural networks (CNN) in deep learning (DL) to detect planetary transits in light curves plagued by red noise.

★ The Adam optimization algorithm may help our discovery of exoplanets. The Adam optimization algorithm was first presented by Diederik Kingma from OpenAI and Jimmy Ba from the University of Toronto in their 2015 International Conference on Learning Representations paper (poster). The method is efficient and requires less memory than some other algorithms when working with large problems involving a lot of data or parameters. (https://www.geeksforgeeks.org/intuition-of-adam-optimizer/).

★ Kim and Choi (2021) indicated that the traditional optimizers used in deep learning still have unsatisfactory training performance for the models with many layers and weights. Accordingly, they proposed a new Adam-based hybrid optimization method for training CNNs effectively.

RESEARCH OBJECTIVE

★ **Research purpose:** The goal of this project is to develop an effective method that utilizes deep learning to find exoplanets among the astronomy big data, such as the NASA Kepler data.

Research Methods (1)

Transit Method

★ In this research, I used the transit method. NASA lists the numbers of exoplanets found thus far by various methods: Transit (3854), Radial Velocity (927), Gravitational Microlensing (130), Direct Imaging (59), and Other (1) (https://exoplanets.nasa.gov/alien-worlds/ways-to-find-a-planet/).

Normalization of Light Curves

★ To start with, I normalized light curves from the Kepler data retrieved from the public NASA Kepler database, then divided the light curve into sections before smoothing each section to its own each optimal smoothing spline.

Application of Deep Learning

★ My research applied deep learning (DL) to analyze the light curves that were recorded by the Kepler telescope to detect transit signals. In my DL program, I used the Adam optimization algorithm from TensorFlow: tf.keras.optimizers.Adam to optimize the values of the model parameters through training my DL program.

Research Methods (2)

Building and Training My Python DL Program and Model

★ Using my own code, open source Python code, and DL packages such as TensorFlow, I built a Python deep learning program to search for exoplanets.

★ With the program, I first created a simulated artificial dataset with transit-like features and the trapezoid method, where varying parameters representing period, duration, depth, and ratio were used to create inverted parallel trapezoids that resembled transit signals.

★ Then, I trained the model with the Adam optimization algorithm to obtain the optimized model parameters. The following figures showed how the model was trained and improved, and reported the final performance result of the testing.

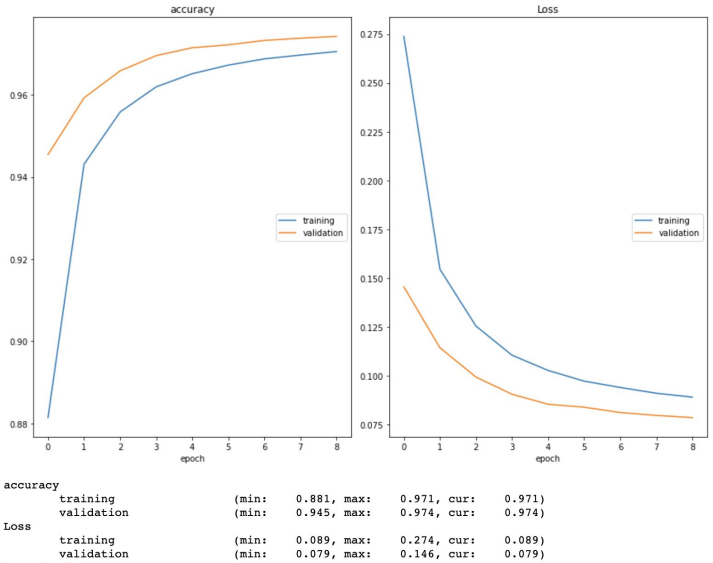


Figure 1. Accuracy and loss through training

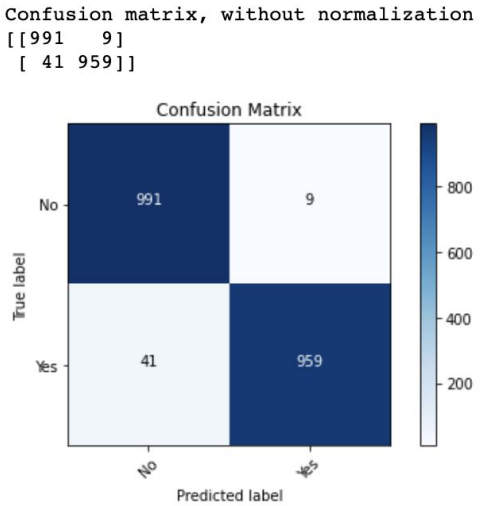


Figure 2. Confusion matrix showing performance of testing

Research Methods (3)

Using My DL Model to Search for Special Exoplanets

★ Subsequently, I folded the normalized light curves with GPU 100,000 times with each period spaced evenly between a set range of days to overlap the transits in the folds to intensify transit signals.

★ Using the deep learning program with the model that I trained, I examined a huge amount of light curves from the Kepler data.

Results (1)

Detection of a New, Previously Undiscovered Possible Exoplanet

★ **This program detected a possible exoplanet** orbiting the star Kepler Input Catalog number (KIC) 5881688, marking the first discovery of this exoplanet. KIC 5881688 is a single main sequence star in the Milky Way approximately 1475±60 parsec away from the Solar system. Figure 3 shows the fold of the transit (the evident U-shape) and its score that out of of 1.0. Table 1 lists the orbital period 0.8381 that indicated this is an ultra-short period exoplanet (USP). Table 2 lists its stellar parameters.

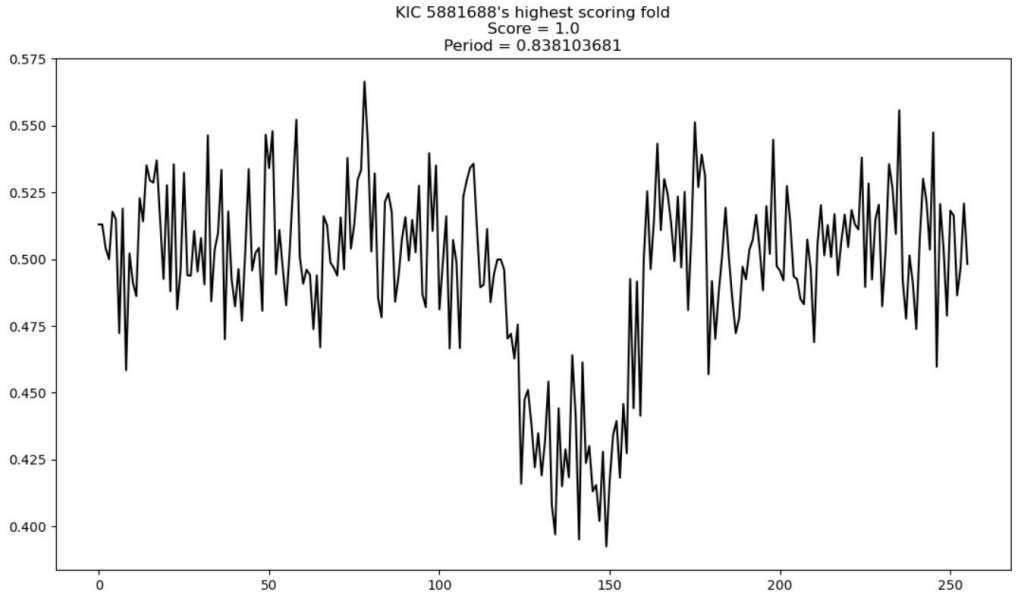


Figure 3. Light curve fold and score of the transit

Variable	Value
Orbital Period (days)	0.838103681
Transit Score	1.0

Table 1. Exoplanet Period

Variable	Value
Stellar Effective Temperature (K)	5903^{+107}_{-160}
Stellar Radius (Solar radii)	$1.08^{+0.29}_{-0.12}$
Stellar Mass (Solar mass)	$1.06^{+0.08}_{-0.07}$

Table 2. Stellar Parameters

Note. Stellar parameters retrieved from the Open Exoplanet Catalogue.

Results (2)

Detection of Another New, Previously Undiscovered Possible Exoplanet

★ **A possible exoplanet** orbiting the star KIC 10024051 was detected by the program. KIC 10024051 is also a star approximately 523±6 parsec away from the Solar system. Figure 4 shows the fold of the transits (the evident U-shapes) and its score. Table 3 lists the orbital period 4.0417 for this short period exoplanet (SP) and Table 4 lists the stellar parameters.

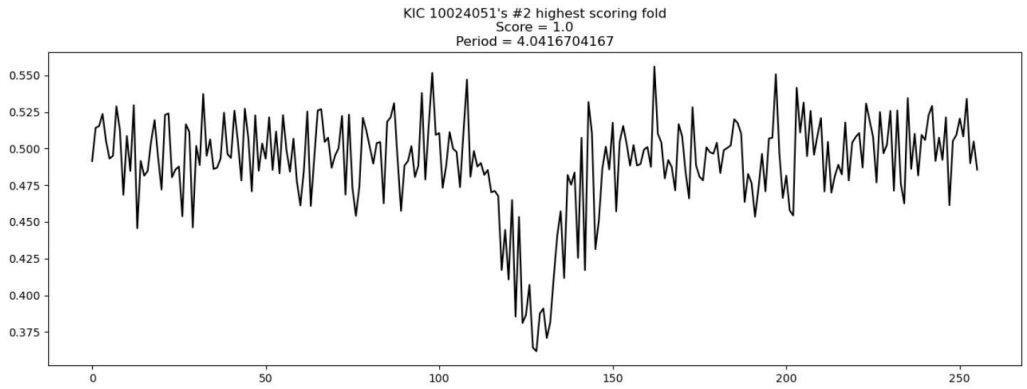


Figure 4. Light curve fold and score of the transit

Variable	Value
Orbital Period (days)	4.0416704167
Transit Score	1.0

Table 3. Exoplanet Period

Variable	Value
Stellar Effective Temperature (K)	5063^{+95}_{-81}
Stellar Radius (Solar radii)	$0.74^{+0.05}_{-0.07}$
Stellar Mass (Solar mass)	$0.78^{+0.05}_{-0.06}$

Table 4. Stellar Parameters

Note. Stellar parameters retrieved from the Open Exoplanet Catalogue.

Results (3)

Detection of Another New, Previously Undiscovered Possible Exoplanet

★ **This program detected the third possible exoplanet** orbiting the star KIC 9595827. KIC 9595827 is a star approximately 940 ± 20 pc away from us. Figure 5 shows the fold of the transit (the evident U-shape) and its score that out of of 1.0. Table 5 lists the orbital period and Table 6 lists its stellar parameters.

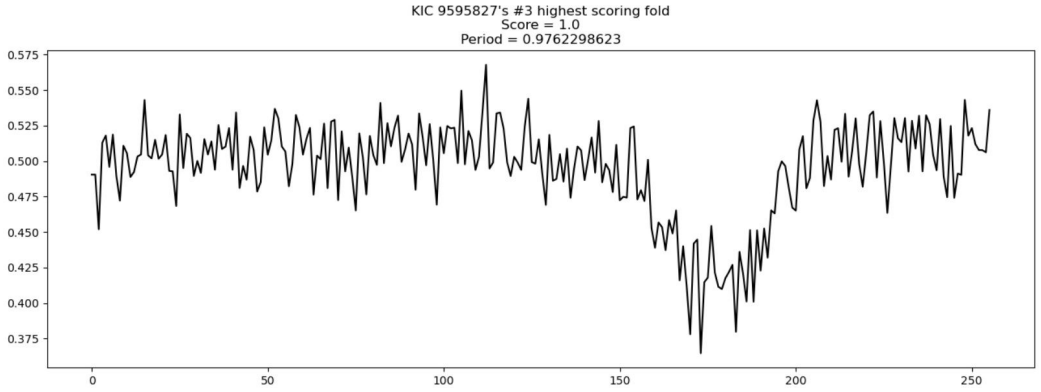


Figure 5. Light curve fold and score of the transit

Variable	Value
Orbital Period (days)	0.9762298623
Transit Score	1.0

Table 5. Exoplanet Period

Variable	Value
Stellar Effective Temperature (K)	5543±138
Stellar Radius (Solar radii)	0.89±0.07
Stellar Mass (Solar mass)	0.92±0.08

Table 6. Stellar Parameters

Note. Stellar parameters retrieved from the Open Exoplanet Catalogue.

Results (4)

Detection of Another New, Previously Undiscovered Possible Exoplanet

★ **Another possible exoplanet** orbiting the star KIC 2692377 was detected by my program. KIC 2692377 is a star approximately 437 parsec away from us. Figure 6 shows the fold of the transit (the evident U-shape) and its score of 1.0. Table 7 lists the orbital period, and Table 8 lists its stellar parameters.

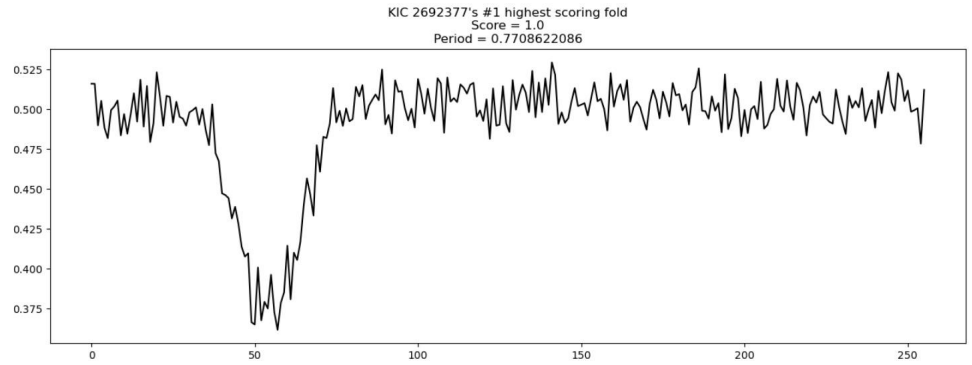


Figure 6. Light curve fold and score of the transit

Variable	Value
Orbital Period (days)	0.7708622086
Transit Score	1.0

Table 7. Exoplanet Period

Variable	Value
Stellar Effective Temperature (K)	5539±73
Stellar Radius (Solar radii)	1.11±0.12
Stellar Mass (Solar mass)	0.99±0.06

Table 8. Stellar Parameters

Note. Stellar parameters retrieved from the Open Exoplanet Catalogue.

Results (5)

Detection of Another New, Previously Undiscovered Possible Exoplanet

★ **Another ultra-short period exoplanet (USP)** orbiting the star KIC 3338885 was detected by my program. KIC 3338885 is a star approximately 431±4 parsec away from us. Figure 7 shows the fold of the transit (the evident U-shape) and its score of 1.0. Table 9 lists the orbital period, and Table 10 lists its stellar parameters.

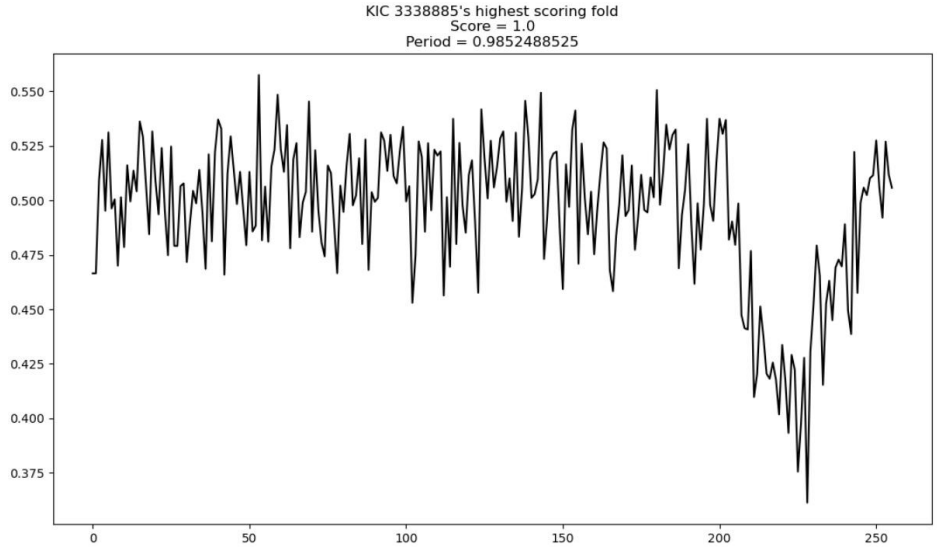


Figure 7. Light curve fold and score of the transit

Variable	Value
Orbital Period (days)	0.9852488525
Transit Score	1.0

Table 9. Exoplanet Period

Variable	Value
Stellar Effective Temperature (K)	4897^{+91}_{-107}
Stellar Radius (Solar radii)	0.75±0.03
Stellar Mass (Solar mass)	0.80±0.04

Table 10. Stellar Parameters

Note. Stellar parameters retrieved from the Open Exoplanet Catalogue.

Results (6)

Detection of Another New, Previously Undiscovered Possible Exoplanet

★ **A short period exoplanet** orbiting the star KIC 10975146 was detected by the program. KIC 10975146 is a star approximately 343±15 parsec away from us. Figure 8 shows the fold of the transits (the evident U-shapes) and its score. Table 11 lists the orbital period and Table 12 lists the stellar parameters.

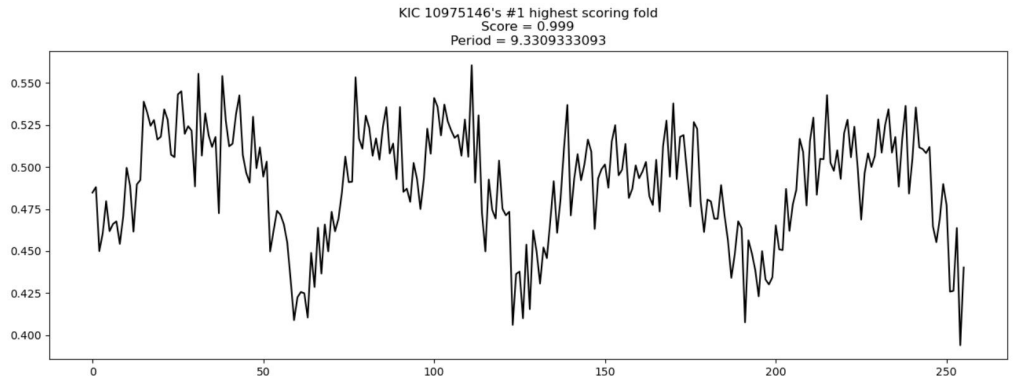


Figure 8. Light curve fold and score of the transit

Variable	**Value**
Orbital Period (days)	2.332733327
Transit Score	0.999

Table 11. Exoplanet Period

Variable	Value
Stellar Effective Temperature (K)	4653^{+51}_{-57}
Stellar Radius (Solar radii)	$0.76^{+0.03}_{-0.05}$
Stellar Mass (Solar mass)	$0.71^{+0.02}_{-0.04}$

Table 12. Stellar Parameters

Note. Stellar parameters retrieved from the Open Exoplanet Catalogue.

Results (7)

Detection of Another New, Previously Undiscovered Possible Exoplanet

★ **Another ultra-short period exoplanet (USP)** orbiting the star KIC 4770365 was detected by my model. KIC 4770365 is a star 543.444+10.777-10.373 parsec away from us. Figure 9 shows the fold of the transit (the evident U-shape) and its score of 1.0. Table 13 lists the orbital period, and Table 14 lists its stellar parameters.

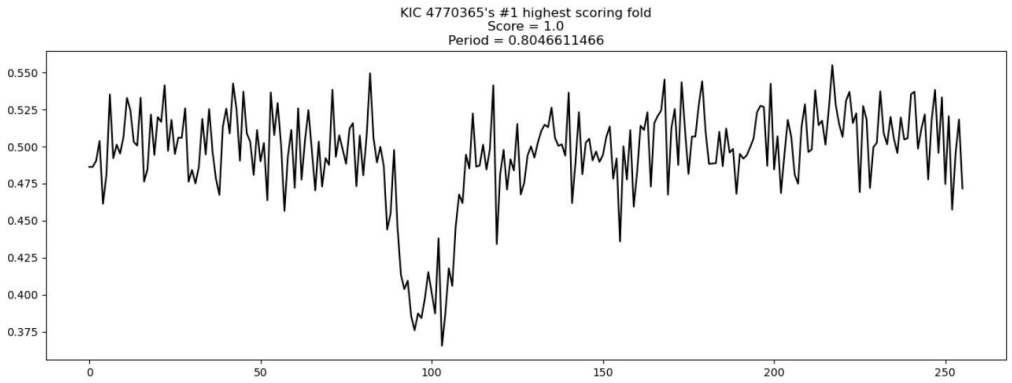


Figure 9. Light curve fold and score of the transit

Variable	Value
Orbital Period (days)	0.8046611466
Transit Score	1.0

Table 13. Exoplanet Period

Variable	Value
Stellar Effective Temperature (K)	4303.0±122.0
Stellar Radius (Solar radii)	0.714145
Stellar Mass (Solar mass)	0.67

Table 14. Stellar Parameters

Note. Stellar parameters retrieved from the NASA Exoplanet Archive.

Results (8)

Detection of Another New, Previously Undiscovered Possible Exoplanet

★ **Another ultra-short period exoplanet (USP)** orbiting the star KIC 6871071 was detected by my program. KIC 6871071 is a star that may have 3 short period (1.90 days, 3.28 days, and 5.03 days respectively) exoplanets. Figure 10 shows the fold of the transit (the evident U-shape). Because the transit seems shallow, it may be a false positive or error. Table 15 lists the orbital period, and Table 16 lists its stellar parameters. KIC 6871071 is about 951 parsec away from us.

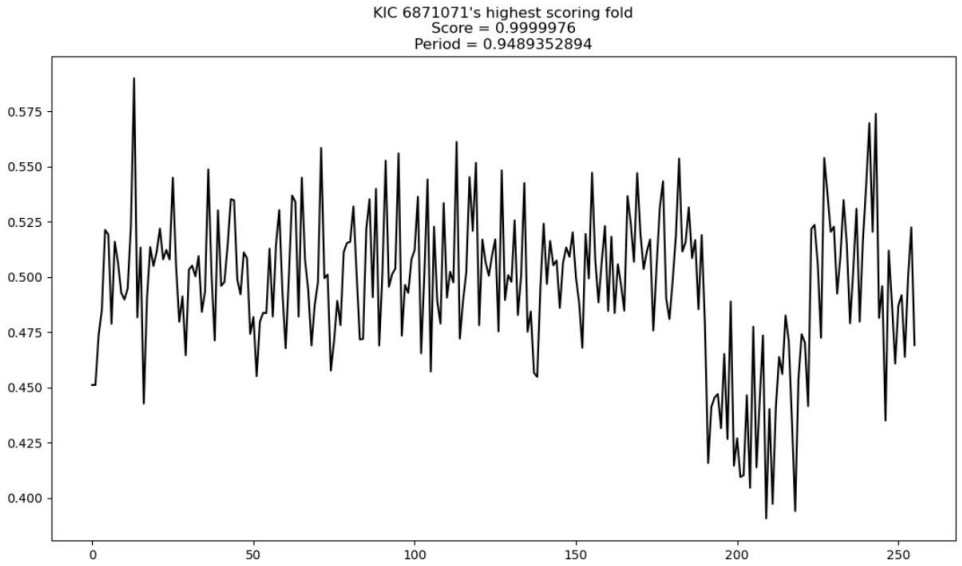


Figure 10. Light curve fold and score of the transit

Variable	Value
Orbital Period (days)	0.9489352894
Transit Score	0.9999976

Table 15. Exoplanet Period

Variable	Value
Stellar Effective Temperature (K)	5977±200
Stellar Radius (Solar radii)	0.9±0.5
Stellar Mass (Solar mass)	1.03±0.11

Table 16. Stellar Parameters

Note. Stellar parameters retrieved from the Open Exoplanet Catalogue.

Results (9)

Detection of Another New, Previously Undiscovered Possible Exoplanet

★ **Another ultra-short period exoplanet (USP)** orbiting the star KIC 6922244 was detected by my program. KIC 6922244 is a star 1330±180 parsec away from us, and located in the constellation Lyra. Figure 11 shows the fold of the transit (the evident U-shape) and its score of 1.0. Table 17 lists the orbital period, and Table 18 lists its stellar parameters.

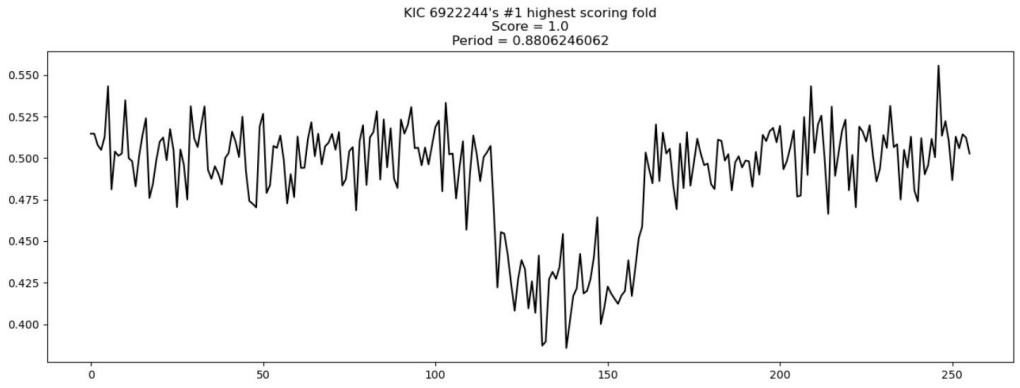


Figure 11. Light curve fold and score of the transit

Variable	Value
Orbital Period (days)	0.8806246062
Transit Score	1.0

Table 17. Exoplanet Period

Variable	Value
Stellar Effective Temperature (K)	6251±75
Stellar Radius (Solar radii)	$1.45^{+0.12}_{-0.13}$
Stellar Mass (Solar mass)	$1.13^{+0.09}_{-0.10}$

Table 18. Stellar Parameters

Note. Stellar parameters retrieved from the Open Exoplanet Catalogue.

Results (10)

Detection of Another New, Previously Undiscovered Possible Exoplanet

★ **A possible ultra-short period exoplanet (USP)** orbiting the star KIC 7825899 was detected by my model. KIC 7825899 is a K-type star approximately 851 pc away from us with two Neptune-sized candidates with a 6.3 day and 16.2 day orbit. Figure 12 shows the fold of the transit (the evident U-shape) and its score. Table 19 lists the orbital period, and Table 20 lists its stellar parameters. Because the transit seems shallow, it may be a false positive or error. However, I am still reporting this detection for further investigation because at this stage, we cannot eliminate the possibility of it being an ultra short period exoplanet.

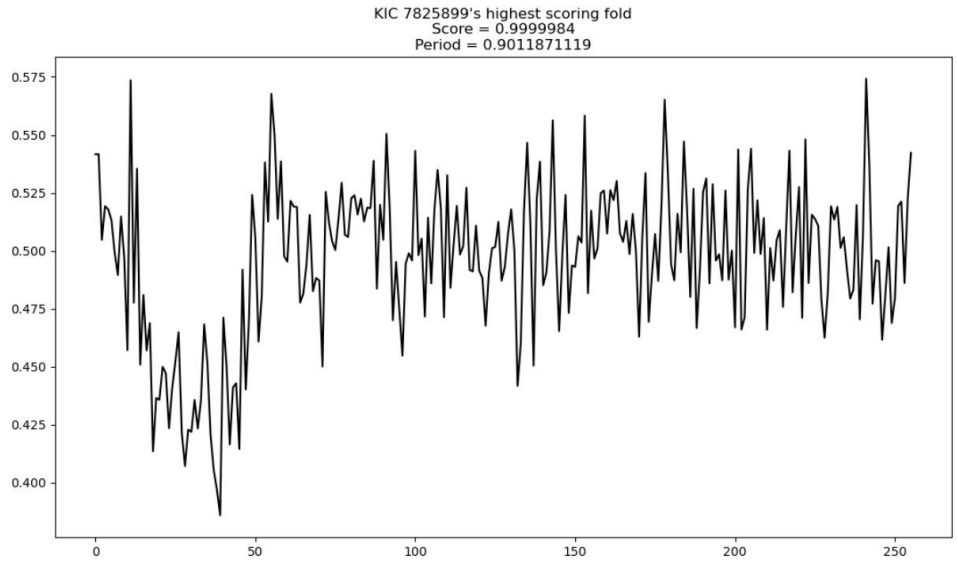


Figure 12. Light curve fold and score of the transit

Variable	Value
Orbital Period (days)	0.9011871119
Transit Score	0.9999984

Table 19. Exoplanet Period

Variable	Value
Stellar Effective Temperature (K)	5175.0±25.0
Stellar Radius (Solar radii)	0.768535
Stellar Mass (Solar mass)	0.88

Table 20. Stellar Parameters

Note. Stellar parameters retrieved from the Open Exoplanet Catalogue.

Results (11)

Detection of Another New, Previously Undiscovered Possible Exoplanet

★ **Another ultra-short period exoplanet (USP)** orbiting the star KIC 7871954 was detected by my program. KIC 7871954 is a star approximately 192.3 parsec away from us. Figure 13 shows the fold of the transit (the evident U-shape) and its score of 1.0. Table 21 lists the orbital period, and Table 22 lists its stellar parameters.

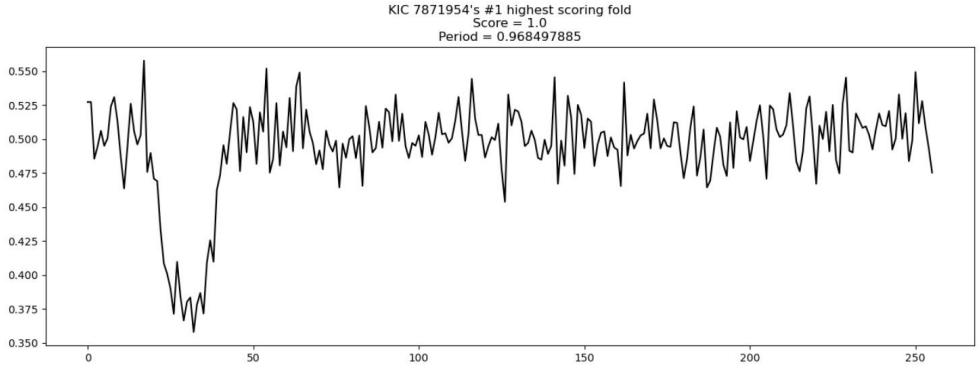


Figure 13. Light curve fold and score of the transit

Variable	Value
Orbital Period (days)	0.968497885
Transit Score	1.0

Table 21. Exoplanet Period

Variable	Value
Stellar Effective Temperature (K)	3944^{+150}_{-50}
Stellar Radius (Solar radii)	0.48±0.03
Stellar Mass (Solar mass)	0.575±0.016

Table 22. Stellar Parameters

Note. Stellar parameters retrieved from the Open Exoplanet Catalogue.

Results (12)

Detection of Another New, Previously Undiscovered Possible Exoplanet

★ **Another ultra-short period exoplanet (USP)** orbiting the star KIC 12470954 was detected by my program. KIC 12470954 is a star approximately 704±9 parsec away from us. Figure 14 shows the fold of the transit (the evident U-shape) and its score of 1.0. Table 23 lists the orbital period, and Table 24 lists its stellar parameters that were retrieved from Open Exoplanet Catalogue.

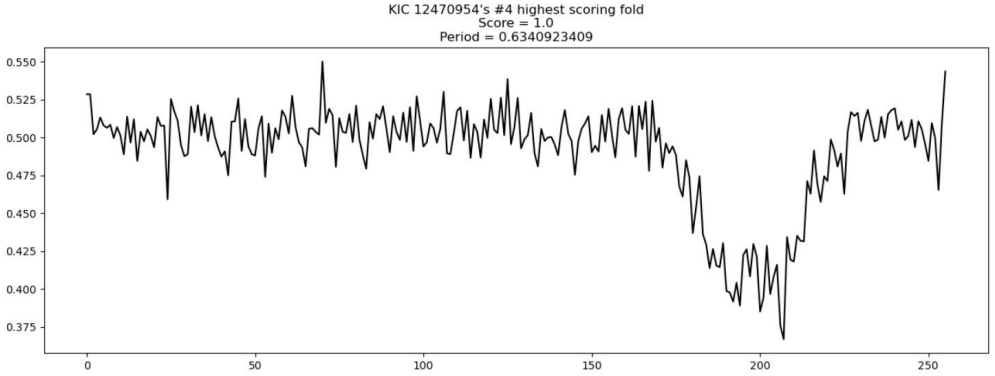


Figure 14. Light curve fold and score of the transit

Variable	Value
Orbital Period (days)	0.6340923409
Transit Score	1.0

Table 23. Exoplanet Period

Variable	Value
Stellar Effective Temperature (K)	5447^{+76}_{-67}
Stellar Radius (Solar radii)	$0.92^{+0.06}_{-0.04}$
Stellar Mass (Solar mass)	$0.93^{+0.04}_{-0.03}$

Table 24. Stellar Parameters

Note. Stellar parameters retrieved from the Open Exoplanet Catalogue.

Results (13) - Capable of Detecting Confirmed Exoplanets

★ My DL program was able to detect all of the confirmed USP exoplanets that I tested and many of the confirmed short period exoplanets listed in the NASA database. A sample of them is listed below.

★ This demonstrates that this program has the capability to discover real and confirmed exoplanets, implying that these newly detected exoplanets are valid possible exoplanets.

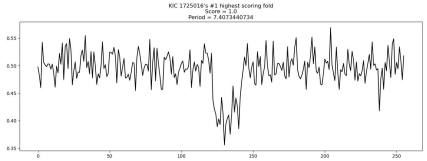
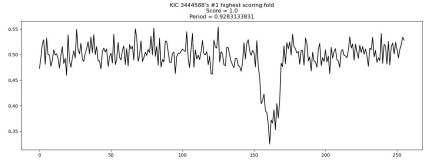
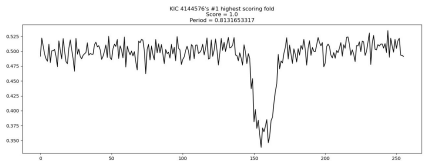
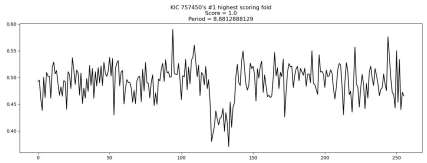
	The results of my program		**NASA data**
KIC	**Period (days)**	**Transit**	**Period (days)**
1725016	**7.407**3440734		**7.407**42502 (Kepler-748 b)
3444588	**0.92831**33831		**0.92831**0036 (Kepler-787 b)
4144576	**0.81316**53317		**0.81316**6357 (Kepler-1139 b)
757450	**8.88**12888129		**8.88**4922995 (Kepler-75 b)

Table 25. Sample exoplanets previously found and confirmed in the NASA database that were detected by my program.

Results (14) - Capable of Detecting Confirmed Exoplanets (cont.)

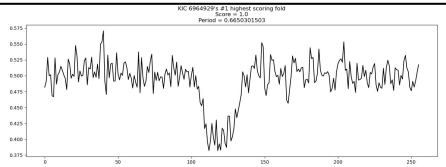
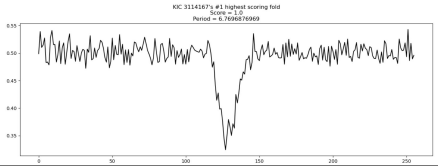
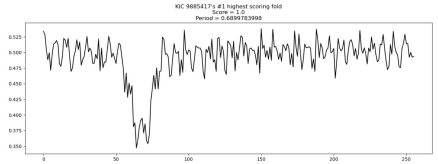
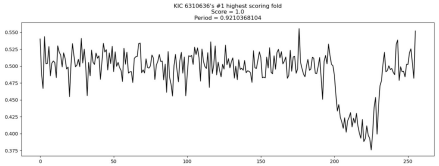
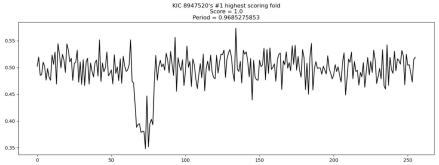
	The results of my program		NASA data
KIC	**Period (days)**	**Transit**	**Period (days)**
6964929	**0.6650**301503		**0.6650**25941 (Kepler-1340 b)
3114167	**6.7**696876969		**6.7**70300385 (Kepler-684 b)
9885417	**0.6899**783998		**0.6899**67868 (Kepler-1340 b)
6310636	**0.92103**68104		**0.92103**0497 (Kepler-929 b)
8947520	**0.968527**5853		**0.968527**683 (Kepler-1264 b)
I can provide other confirmed exoplanets that were also detected by my DL program per request. My program appeared to do a better job for USP exoplanets.			

Table 26. Sample exoplanets previously found and confirmed in the NASA database that were detected by my program.

Results (15)

★ My program also discerned hundreds of other previously discovered candidate exoplanets, which are listed as unconfirmed KOIs (Kepler objects of interest) by NASA.

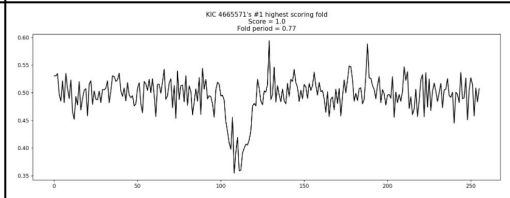
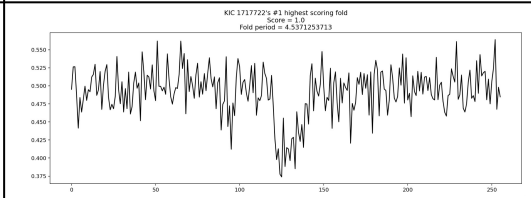
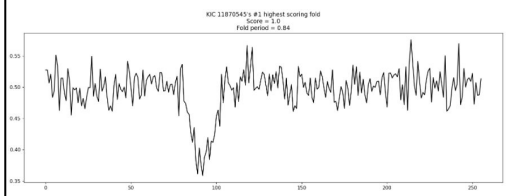
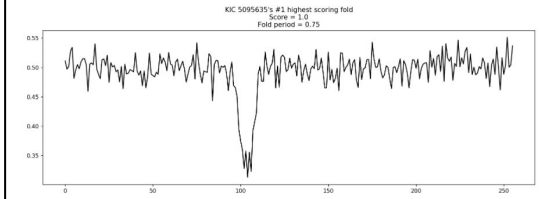
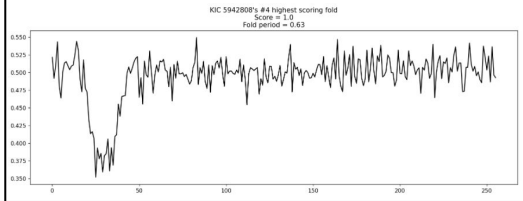
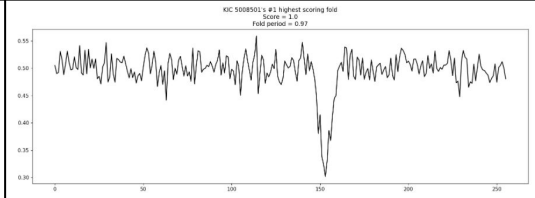
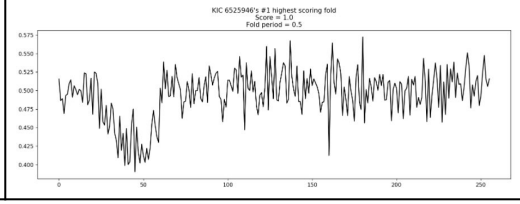
KIC	Period (days)	Transits shown by my program	KIC	Period (days)	Transits shown by my program
4665571	0.77		1717722	4.54	
11870545	0.84		5095635	0.75	
5942808	0.63		5008501	0.97	
6525946	0.50		For other unconfirmed exoplanet candidates that were also detected by my DL program like the ones shown here, I can provide them per request.		

Table 27. Sample exoplanets previously found and listed as candidates by NASA that were discerned by my program.

Discussion (1)

- ★ My program detected 12 new, previously undiscovered exoplanets. One more has been detected and added to the list since the submission of my previous abstract to ESO.
- ★ Because the Kepler mission lasted for 9.6 years and observed each star for a selected period of time, it may be hard to catch transits of the exoplanets with long orbital periods. Thus, there are many more Kepler Objects of Interest (KOI) with shorter orbital periods than those with long orbital periods in the NASA database. This may also be a reason as to why the orbital periods of my detected exoplanets are all shorter than 10 days.
- ★ My program has detected all of the confirmed USP exoplanets that I tested and many short period exoplanets in the NASA database, demonstrating its capability to detect real exoplanets.
- ★ However, the detection of those new, previously undiscovered exoplanets is the first step to discover and confirm those real exoplanets. Further work is needed.

Discussion (2)

★ Meanwhile, the detection of these new exoplanets, especially the USP exoplanets, can shed light on their kind and expand our views on their planetary systems. Finally, these findings show that artificial intelligence such as deep learning can be an effective technological tool to detect objects of interest in astronomy big data.

★ I welcome advisory and comments on my research and would like to join a team for the further work.

Conclusion

★ To conclude, using deep learning with the Adam optimizer, I successful detected more than ten new exoplanets. This marks the first discovery of these exoplanets, and further work is needed, as this project provides exoplanet targets for future investigation.

★ This program is also capable of detecting confirmed and candidate exoplanets listed in the NASA database.

★ The detection of the confirmed, candidate, and new exoplanets of the Python program in this project indicates that artificial intelligence such as deep learning can be an effective technological tool to discover exoplanets within astronomy big data.

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★ I would also like to thank ESO for providing me with such a valuable opportunity to share the results of my research.

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Thank you!

Questions?

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