Using Convolutional Neural Networks to Detect and Confirm Exoplanets

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Abstract

Using deep learning (DL), I developed a Python software program with convolutional neural network (CNN) modules from TensorFlow to detect exoplanets through their transit signals in the National Aeronautics and Space Administration (NASA) Kepler space telescope data. My program first normalizes light curves, then trains deep learning models, tests and evaluates the models with sample data, folds the light curves of real data to intensify the transit signals, and subsequently applies the DL models to find exoplanets. With this program, I detected new exoplanets and found confirming evidence for previously unconfirmed exoplanets with special astrophysical properties. Four of these detected exoplanets are not listed in the KOI (Kepler Object of Interest) list and tens of the exoplanets are ultra-short period (USP) exoplanets, whose orbital periods are shorter than one day. USP exoplanets are important subjects of research in astrophysics because in order to orbit at such close distances from their stars, these USPs demonstrate a few special physical patterns such as tidal interactions and spin evolution, and also challenge some astrophysical explanations. In addition, transit signals of exoplanets with extremely long periods are difficult to find in the Kepler data because the Kepler mission lasted for only 9.6 years and observes each star for a selected period of time. For this reason, there are much more KOIs with shorter periods than those with long periods in the NASA database. However, my deep learning program detected a possible Jupiter-like exoplanet in long orbital period together with two other KOI exoplanet candidates in a star system 592.7110±12.3435 parsec away from Earth. This is the first detection of this Jupiter-like exoplanet. It has an orbital period longer than 1600 days, a radius of 10.637 Earth radii, and a planet-star radius ratio of 0.127314. Similarly, Jupiter also has a radius of 11.209 Earth radii and a planet-star radius ratio of 0.102668. Moreover, the size of the transit signal is ~2%, which is comparable to that of Jupiter. These similar stellar and planetary features all indicate that this newly detected exoplanet is a possible Jupiter-like exoplanet, and this multiplanetary system is a Solar-like system, in that a Solar-like system has at least one Jupiter-like or Saturn-like planet. According to NASA, Jupiter is perhaps the most important planet of our system because as the largest planet in the system, it distorts orbits of comets, knocks asteroids out of their orbits, and its gravity affects the orbits of other planets. This new Jupiter-like exoplanet can help expand our understanding about the impact of a Jupiter-like exoplanet with astrophysical significance in its multiplanetary system that has differences from our Solar system. All of the findings indicate that deep learning is an effective method to detect exoplanets and uncover important evidence on exoplanets in big data, and my program can be built upon and reused by other astronomers.

Research Objective

★ The objective of this project is to develop an effective method that utilizes deep learning such as convolutional neural networks (CNNs) to find exoplanets among astronomy big data such as the NASA Kepler data.

Data and Methods

★ Data: Kepler data retrieved from the public NASA Kepler database.

★ Exoplanet search method: Transit method.

★ Python program: Using my own code, open source Python code, and DL packages TensorFlow, I built a Python deep learning program to search for exoplanets. This program employs the CNN and the Adam optimizer from TensorFlow.

1. 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.
2. Secondly, the program normalized the transit light curves retrieved from the Kepler database.
3. Third, I trained the model with the Adam optimization algorithm to obtain the optimized model parameters for this CNN program. The following Figure 1 shows how the model was trained and improved, and Figure 2 reported the final performance result of the testing.

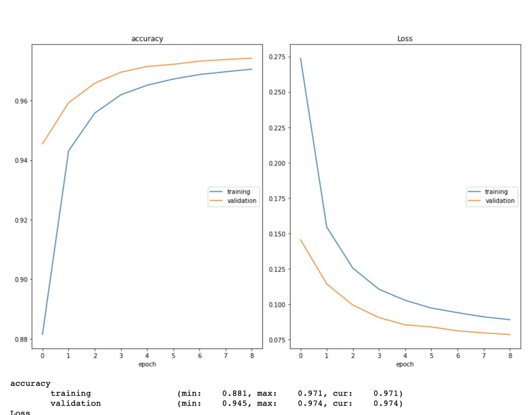


Figure 1

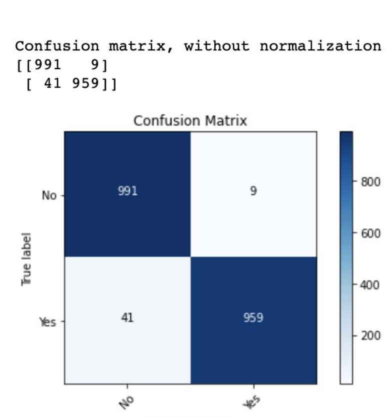


Figure 2

4. Fourth, using this program, I folded the transit light curves to intensify the transit signals.
5. Lastly, I used this DL program employing a CNN to search for exoplanet transits in the Kepler light curves, i.e., to detect exoplanets.

Results - Detection of New Exoplanets

★ Detection of a New, Previously Undiscovered Exoplanet Orbiting KIC 5881688

This program employing a CNN detected an ultra-short period exoplanet (USP) in the stellar system of Kepler Input Catalog (KIC) 5881688, marking the first step of discovery of this exoplanet. Like the Sun, KIC 5881688 is a single main sequence star in the Milky Way. Figure 4 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 and Table 2 lists its stellar parameters. KIC 5881688 is 1475±60 parsec away from us. Its size (1.08 times of the Sun) and mass (1.06 times of the Sun) is very similar to that of the Sun.

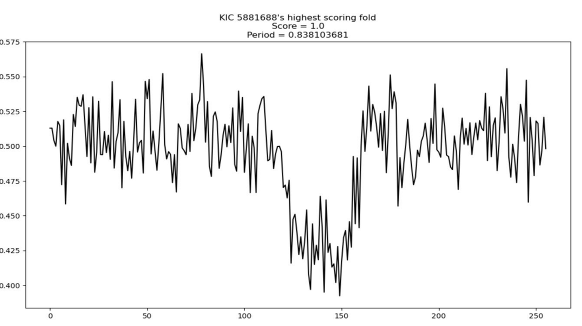


Figure 3. Light curve fold and score of the transit

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.

★ Detection of a Second New, Previously Undiscovered Exoplanet Orbiting KIC 10975146.

The program detected a short period exoplanet (SP) orbiting KIC 10975146, marking the first discovery of this exoplanet. KIC 10975146 is also a single main sequence star. Figure 4 shows the fold of the transit (the evident U-shapes) and its score that out of of 1.0. Table 1 lists the orbital period and Table 2 lists its stellar parameters. KIC 10975146 is 343±15 parsec away from us. Its size (0.76 times of the Sun) and mass (0.71 times of the Sun) is smaller and lighter than that of the Sun.

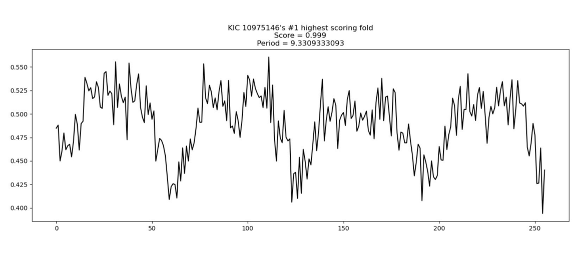


Figure 4. Light curve fold and score of the transit

Variable	Value
Orbital Period (days)	2.332733327
Transit Score	0.999

Table 3: 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 4: Stellar Parameters

Note. Stellar parameters retrieved from the Open Exoplanet Catalogue.

★ Detection of a Possible New Jupiter-like Exoplanet (Further Work Needed)

In the system of KIC 1717722, my program detected a Jupiter-like planet. Figure 7 shows a global view and Figure 8 shows a local view of the transit. Table 4 lists the parameters for this transit exoplanet using a fitting program to calculate. However, because only one light curve was detected, and we cannot exclude the possible of data error or confirm this is an authentic Jupiter-like Exoplanet, further work on this exoplanet is needed. Since the light curve signal is so big that even a terrestrial telescope on earth may be able to catch its transit signal for the confirmation.

The transit covered 2% of the star flux, which shows that the size of the planet is similar to that of Jupiter. Out of 1600 days that the Kepler data surveyed for this star, the transit only appeared once, so its period is greater than 1600 days. Its radius is 10.637 Earth radii, close to the radius of Jupiter in our Solar System that is 11.209 times of Earth's. The planet-star radius ratio of Jupiter to the Sun is 0.102667942 while the planet-star radius ratio of this exoplanet to its star is 0.12731395. The size of the transit signal (2%), its comparable size to Jupiter, and the similar stellar features of its star all indicate this exoplanet detected in this research is a Jupiter-like exoplanet.

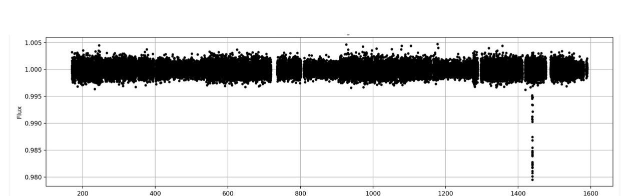


Figure 5. Global view of normalized light curve with transit

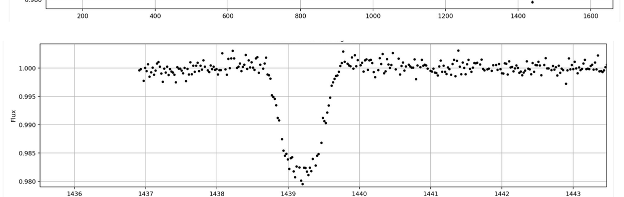


Figure 6. Local view of normalized light curve of transit

Parameter	Value
Transit Epoch (days)	1439.18583
Inclination (deg)	89.9203216
Planet-Star Radius Ratio	0.12731395
Planet Radius (Earth radii)	10.637
Limb Darkening Coefficient 1	0.98352617
Limb Darkening Coefficient 2	0.41136921

Table 5: Jupiter-like Planet Transit Parameters

★ Detection of Another New, Previously Undiscovered Exoplanet Orbiting KIC 9595827.

The program detected an ultra-short period exoplanet orbiting KIC 9595827. KIC 9595827 is a star approximately 940 ± 20 parsec away from us. Figure 4 shows the fold of the transit (the evident U-shapes) and its score that out of of 1.0. Table 1 lists the orbital period and Table 2 lists its stellar parameters. KIC 9595827 is. Its size (0.89 times of the Sun) and mass (0.92 times of the Sun) is smaller and lighter than that of the Sun.

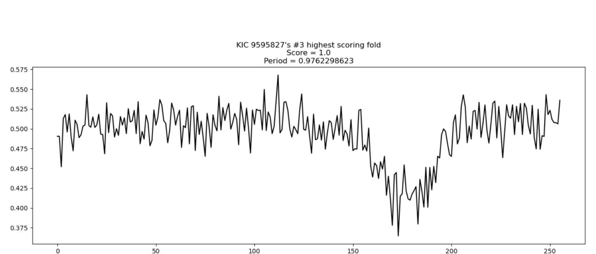


Figure 7. Light curve fold and score of the transit

Variable	Value
Orbital Period (days)	0.9762298623
Transit Score	1.0

Table 6: 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 7: Stellar Parameters

Note. Stellar parameters retrieved from NASA Kepler database.

Results - Detection of Confirmed & Candidate Exoplanets

★ My program also discerned hundreds of confirmed and previously discovered unconfirmed candidate exoplanets listed by the NASA database.
(Due to the limitations on this presentation, I can only present several of them here.)

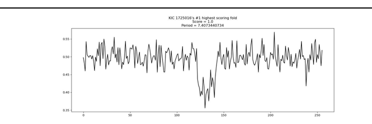
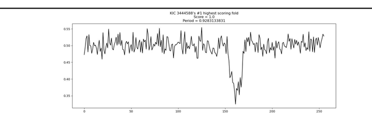
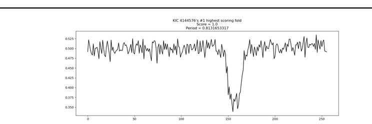
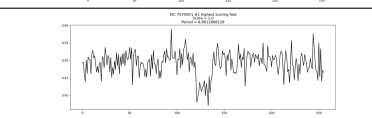
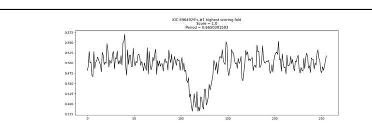
	The results of my program			NASA data
KIC	Period (days)	Transit signal		Period (days)
1725016	**7.4073**440734			**7.407**42502 (Kepler-748 b)
3444588	**0.92831**33831			**0.928310**036 (Kepler-787 b)
4144576	**0.81316**53317			**0.81316**6357 (Kepler-1139 b)
757450	**8.88**12888129			**8.88**4922995 (Kepler-75 b)
6964929	**0.6650**301503			**0.6650**25941 (Kepler-1340 b)

Table 8: Detection of Confirmed Exoplanets

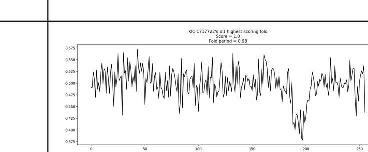
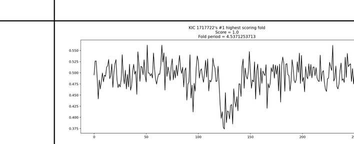
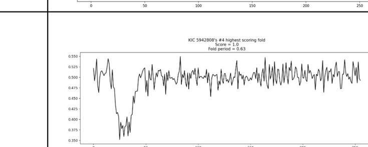
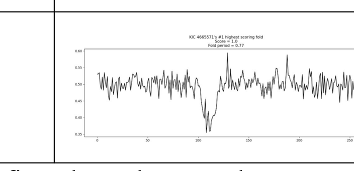
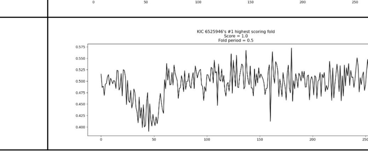
KIC (Candidate)	Period (days)	Transit	KIC (Candidate)	Period (days)	Transit
1717722	0.97		1717722	4.54	
5942808	0.63		4665571	0.77	
6525946	0.50		Hundreds of other confirmed exoplanets and unconfirmed exoplanet candidates like the ones shown here were also detected by my DL program. I can provide them per request.		

Table 9: Detection of Unconfirmed Exoplanet Candidates

Discussion

My program detected several new, previously undiscovered exoplanets. This is the first step to discover and confirm those planets outside our solar system. The exoplanets detected in this project especially the possible Jupiter-like exoplanet need further evaluation.

Because the Kepler mission lasted for 9.6 years and observed each star for a selected period of time, it is 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 most of my detected exoplanets are shorter than 10 days.

Besides the new exoplanets that I detected, this program employing CNN was able to discern hundreds of the previously discovered, especially those confirmed, exoplanets in the Kepler data, demonstrating its capability to detect real exoplanets

The results of this research indicate that using deep learning such as CNN, we are able to detect exoplanets effectively, which supports the research hypothesis.

Conclusion

To conclude, the results of this project demonstrated that CNN is an effective or feasible method to discover exoplanets within astronomy big data, such as the Kepler data. Using a program that utilizes CNN, I successful detected four new exoplanets. This marks the first discovery of those planets beyond our solar system. However, further work on these new exoplanets is needed to evaluate whether the detection came from false positives or resulted from signals of real exoplanets. This is for future work.

The detection and further investigation of these new exoplanets may help expand our understanding of the properties of these planets in their star systems and our theories on the universe. In addition, the results of this research can also help expedite our discovery of new exoplanets and contribute to our space exploration journey.

Acknowledgement

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Key References

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