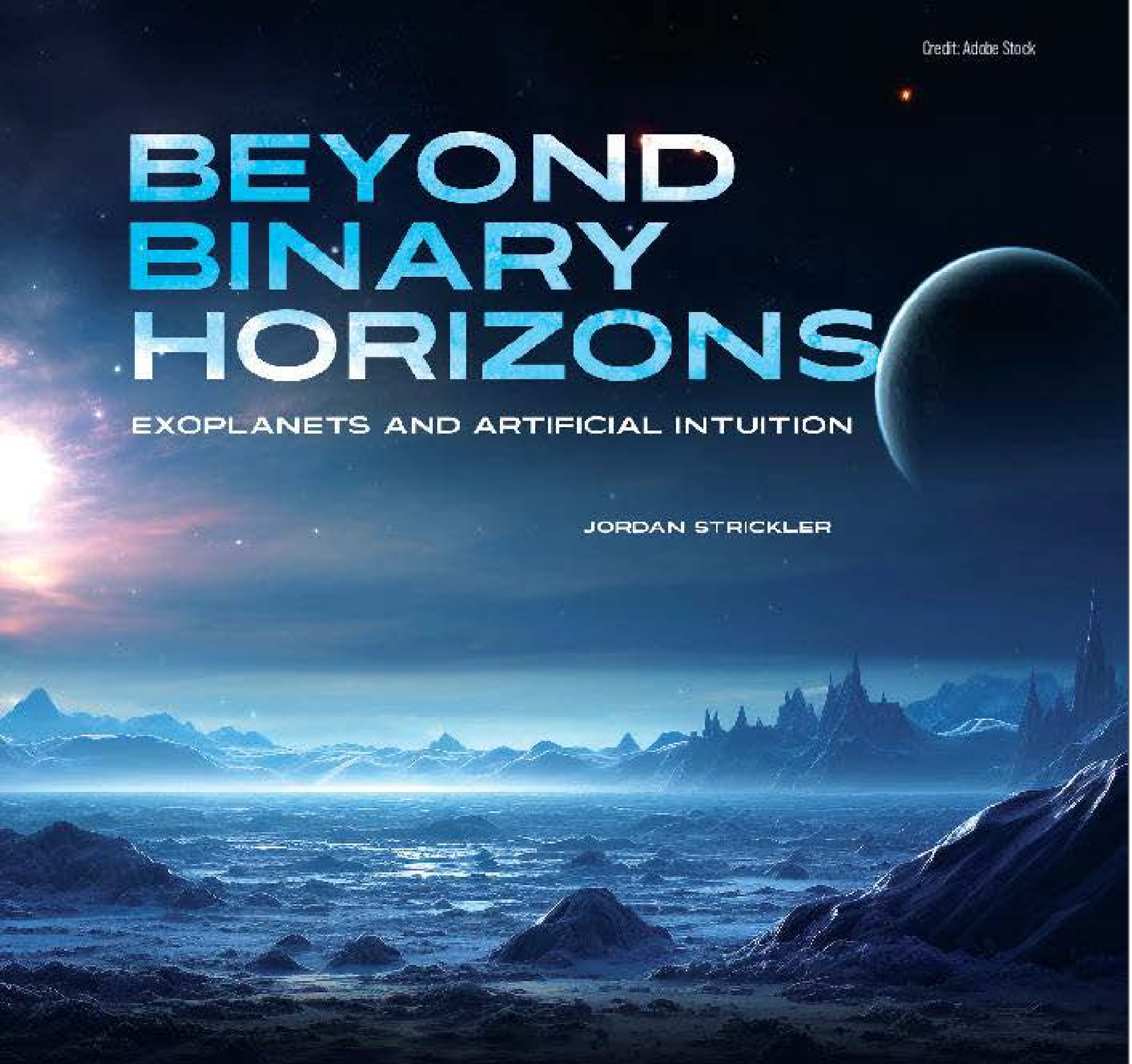

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BEYOND BINARY HORIZONS

EXOPLANETS AND ARTIFICIAL INTUITION

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In the latter part of the 20th century, a dedicated cadre of astronomers embarked on a scientific odyssey. Their holy grail was finding the first planet orbiting a star similar to the sun. As the 1980s gave way to the 1990s, a pivotal moment in this astronomical saga unfolded.

The breakthrough occurred when radio astronomers Aleksander Wolszczan and Dale Frail turned their focus to PSR B1257+12, a pulsar located 2,300 light-years away. Pulsars, being incredibly precise cosmic clocks, allow for small anomaly detection in their emitted signals, which could indicate the presence of orbiting bodies.

As the duo monitored the pulsar using the radio velocity method, they noticed minute, yet regular deviations in its pulse timing. This was unusual because pulsars are known for their extremely routine pulses. The deviations observed in PSR B1257+12's pulses suggested that something was exerting a gravitational influence on it, which could be a sign of an orbiting object.

After thorough analysis, the astronomers concluded the irregularities in the pulsar's timing were caused by the gravitational pull of two planets. These planets, they estimated, had masses approximately three and four times that of Earth and orbited the pulsar every 67 and 98 days, respectively. The pair had found their grail.

The possible discovery of the first exoplanet marked a decisive moment in astronomy, and was a precursor to the thousands of exoplanet findings that followed. It laid the groundwork for future research and spurred interest in the hunt for planets around other types of stars, particularly main-sequence stars like the sun. The first confirmed detection of exoplanets around a main sequence star would come three years later, but the 1990 discovery was a crucial and foundational step in the field of exoplanetary research.

Today, exploring exoplanets stands as one of astronomy's most vibrant and intriguing fields, and there are already over 5,500 confirmed planets. What was once a purely theoretical area has rapidly evolved, with each discovery bringing fresh insights. Astronomers have moved from detecting giant gas planets to finding Earth-sized planets and planets in habitable zones. However, with more powerful telescopes such as the Kepler Space Telescope and TESS (Transiting Exoplanet Survey Satellite), there's a lot more data to digest and analyze—and this is where AI comes into play.

"Telescopes are producing vast amounts of data that you have to shovel through," said Distinguished Professor of Astronomy Chris Impey at the University of Arizona. "That's very time-consuming, and then you have the follow-up. You don't want to waste your time. After AI narrows down potential planets, humans can look at interesting things like atmospheres and moons."

AI can help to sort out these intriguing objects in record time. Historically, exoplanet identification was a painstaking process tethered to manual data analyses, but the introduction of AI has changed this narrative. By training computers to recognize complex patterns, AI has become a powerful ally in detecting exoplanets, particularly those resembling Earth. The process uses advanced algorithms, including machine learning and neural networks.

There are various types of machine learning used for hunting exoplanets. NASA's Kepler data analysis system is a good example, incorporating various machine learning techniques to process data from the space telescope of the same name, and has been instrumental in vetting exoplanet candidates from the deluge of data Kepler provided (NASA retired Kepler in 2018).

Neural networks stand at the forefront of this transformation and mark a significant departure from traditional techniques, usually involving small armies of graduate students. Deep learning neural networks, particularly convolutional neural networks, are a special type of neural network that roughly imitates some aspects of human vision and have become integral in this arena. Trained on labeled datasets of light curves, these networks are adept at learning patterns associated with exoplanets, making them highly effective for classifying potential new worlds.

"For the past 20 years, astronomers have used neural networks which give researchers the ability to discern subtle patterns in vast datasets," Impey said. "This has been instrumental in spotting Earth-sized planets, often obscured by stellar noise and variability."

In 2012, AI analysis for astronomy experienced a quantum leap when University of Toronto researchers developed an AI model that surpassed the best image recognition algorithms by a large margin. The new AI system, which became known as AlexNet (named after its main creator, Alex Krizhevsky), won the 2012 ImageNet computer vision contest with an amazing 85 percent accuracy. Convolutional neural networks were at the heart of AlexNet.

The Kepler Space Telescope, prior to launch
Credit: NASA

Artist's impression of exoplanet 55 Cancri
Credit: NASA

However, newer programs provide even greater accuracy. AstroNet, a joint creation by Google and researchers at the University of Texas at Austin, is a deep learning algorithm tailored for classifying potential exoplanets in light curves captured by telescopes. Renowned for its efficiency, AstroNet excels in processing large datasets with high accuracy.

Astronet-Triage-v2 is the latest upgrade in the Astronet series, initially developed for the Kepler mission and later adapted for the K2 extended Kepler mission and TESS missions. This iteration offers substantial improvements over its predecessor. Key enhancements include a larger and more diverse training set, a wider range of classifications, and the use of over 10 times more unique views to analyze transit signals.

In performance tests, Astronet-Triage-v2 showed a higher success rate in correctly identifying TESS objects of interest compared to the original Astronet-Triage. Specifically, it achieved an 86 percent recall rate—the system's ability to correctly identify a specific category of objects—surpassing the 82 percent recall of its predecessor. While this may seem a moderate improvement, this improved accuracy is particularly notable in analyzing signals from fainter stars.

Although it is currently unable to differentiate between eclipsing binaries and transiting planets, Astronet-Triage-v2 serves as an effective preliminary automated screening tool. Plans are underway to further refine and develop it into a comprehensive, fully automated vetting system for planet discovery.

Chris Shallue, a senior software engineer at Google specializing in AI, emphasizes that machine learning integration into exoplanet research shouldn't be a concern for astronomy professionals. He suggests that this technological advancement is meant to augment, not replace, human expertise in the exploration and study of exoplanets.

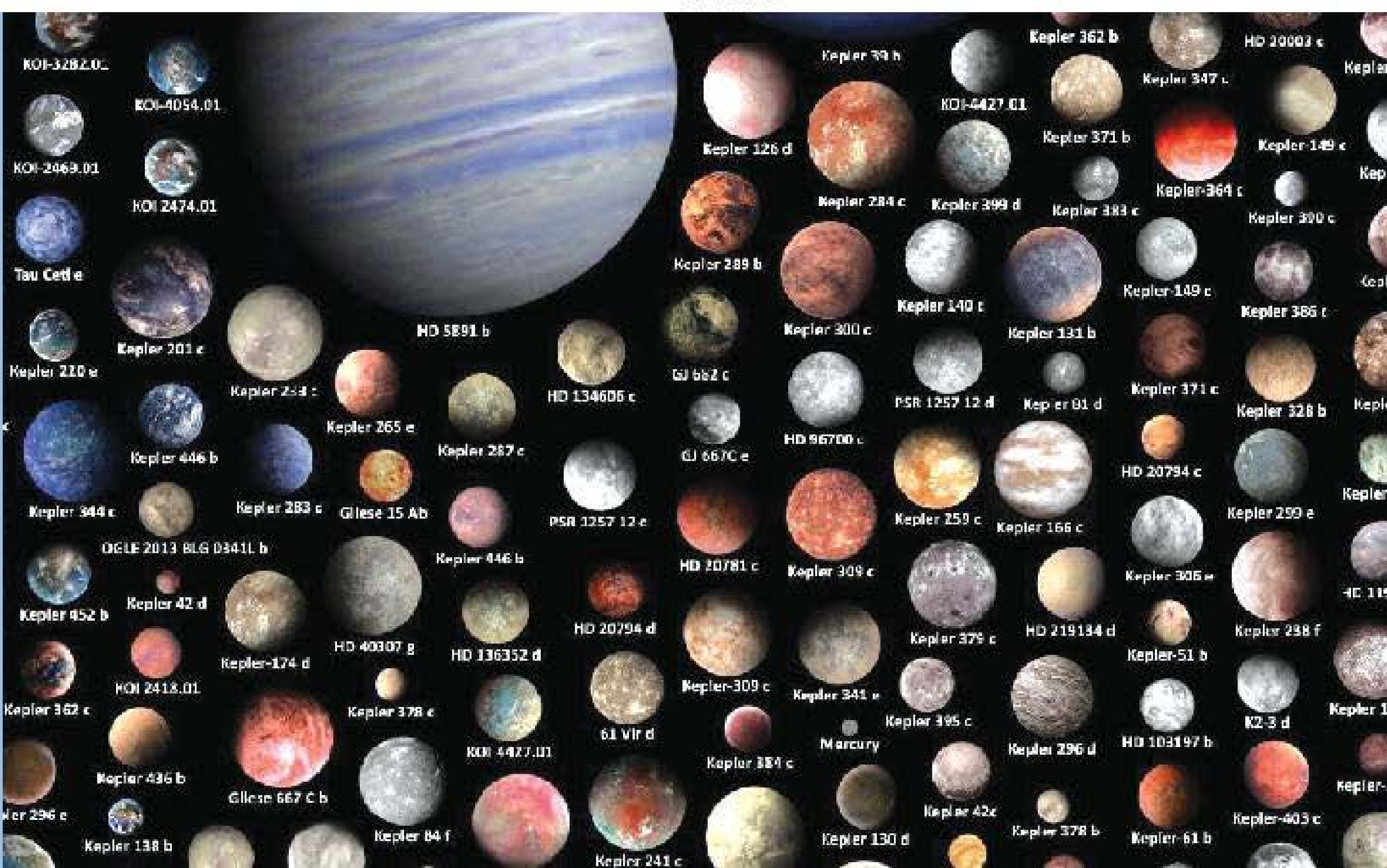
"What we've developed here is a tool to help astronomers have more impact," Shallue said in 2017. "It's a way to increase the productivity of astronomers. It certainly won't replace them at all."

ExoMiner, a more recent addition to NASA's toolkit, is a machine learning algorithm adept at analyzing data from TESS and other missions. Its ability to distinguish between real exoplanet signals and false positives again surpasses previous methods, significantly advancing exoplanet detection. ExoMiner is designed to simulate an exoplanet hunter's decision-making process, helping them to analyze transit signals to vet their authenticity. The program has verified 301 new exoplanets from the MAST Kepler Archive (a vast database of observational data) and is adaptable enough for use in other missions like TESS.

Data shows ExoMiner surpassing existing models in accurately classifying transit signals. For example, ExoMiner identifies 93.6 percent of exoplanets in the test set—data collection used to evaluate the model performance—compared to 76.3 percent by the best previous classifier.

Kepler Robovetter, an automated software used extensively in the Kepler mission, attempts to validate exoplanet candidates by scrutinizing their light curves. It plays a crucial role in determining whether candidates are genuine planets.

An artist-generated catalg of exoplanets, rendered according to suspected characteristics. This type of mapping has accelerated dramatically using artificial intelligence
Credit: NASA



Another program, coined VESPA (Validation of Exoplanet Signals using a Probabilistic Algorithm), serves as a statistical tool for assessing the false positive probabilities of exoplanet candidates. VESPA confirms the planetary nature of detected signals, providing a statistical backbone to the discovery process.

AI's impact isn't limited to space-based telescopes. It also significantly enhances the capabilities of ground-based observatories. These facilities, equipped with state-of-the-art instruments, confirm and further explore the findings of space telescopes. AI's role in processing and analyzing data from these observatories is vital for a comprehensive understanding of exoplanets.

AI algorithms are adept at discriminating noise from the subtle signals of exoplanets, such as the slight dimming of a star when a planet transits in front of it or the tiny gravitational wobble of a star caused by an orbiting planet. While conceptually simple, such detection methods involve analyzing enormous amounts of data to find these faint signals. AI excels in this task, significantly improving the speed of exoplanet detection.

A major strength of AI lies in its unparalleled ability to sift through terabytes of astronomical data and then identify patterns and anomalies suggesting an exoplanet's presence. This capability has led to a substantial increase in the number of known exoplanets and has fundamentally changed the landscape of astronomical research.

"A decade ago, we used to write very prescriptive code to search for dips in light curves, indicative of planets passing in front of stars," said California Institute of Technology astrophysicist Jessie Christiansen, one of the leading exoplanet discoverers and the lead scientist for NASA's Exoplanet Archive. "But with machine learning, we feed it data we know contains these dips and let it find similar patterns in new data. This approach has significantly improved the efficiency of identifying potential exoplanets."

Integrating AI into exoplanet research has also fostered collaborations across various fields, bringing together astronomers, computer scientists, and statisticians. These teams work together to refine AI algorithms, enhancing their efficiency and precision. As the technology evolves, it's poised to play an even more crucial role in future space missions and deep space astronomy.

AI's applications in astronomy extend beyond identifying exoplanets and is instrumental in analyzing the composition of exoplanet atmospheres, searching for exomoons, and assessing the potential habitability of distant worlds. This broader application is opening new frontiers in the quest to understand the cosmos.

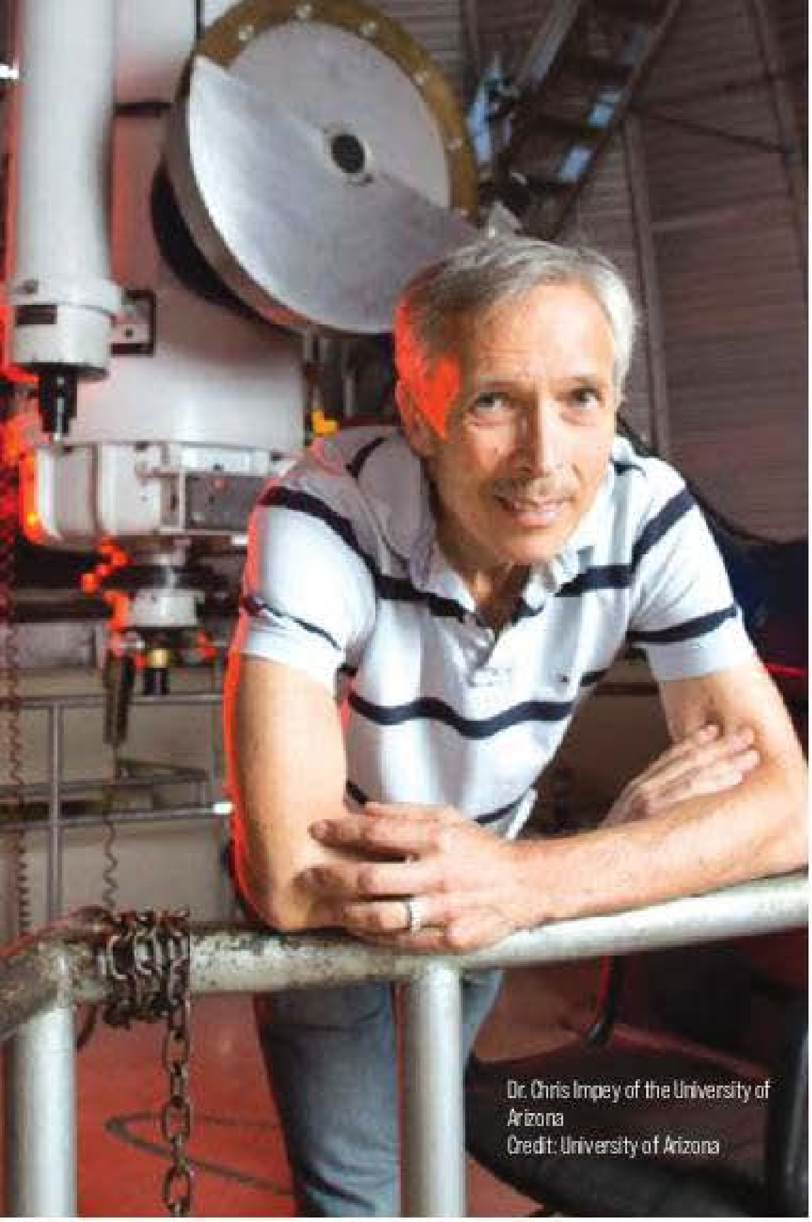
While the integration of AI into astronomy offers numerous advantages, it also presents challenges. Developing accurate and reliable AI algorithms requires extensive, well-curated datasets and continuous refinement. However, the opportunities in deepening humanity's knowledge are immense and unprecedented.

The use of AI is growing throughout astronomical research. It enables astronomers to conduct more targeted observations, focusing telescope time on the most promising exoplanet candidates. This optimization is crucial since telescope time is highly valuable, can be extremely expensive, and is often quite limited.

Another major application of AI mentioned by Christiansen is stellar classification. "We used a machine learning algorithm to classify stars based on their spectra and colors. With only a subset having detailed spectral data, the algorithm helped classify the rest, identifying different types like M dwarfs, G stars, and F stars."

This ability to process and categorize large volumes of data quickly has been invaluable, as manual classification is not only time-consuming but also less consistent because people are, well, human.

Artist's impression of exoplanet Kepler 186f, discovered by parsing three years of Kepler Space Telescope data. AI will greatly reduce the time required to find such new worlds
Credit: NASA



Dr. Chris Impey of the University of Arizona
Credit: University of Arizona

Christiansen also highlights the dynamic evolution of AI in astronomy. "The machine learning algorithm we used on the Kepler data found 300 candidates that humans hadn't found. It's already proving more efficient in certain tasks, and its capabilities are continuously improving."

Moreover, Christiansen sees AI as a tool that could potentially redefine the role of astronomers. She reflects on how AI already impacts her daily workflow, especially in literature review. "AI helps classify and rank newly published papers in astronomy, focusing on exoplanet research. This used to take me hours every day, but now I can just review the top-ranked papers," she explains. "We're still in a period of discovery, figuring out what tasks machine learning excels at and what still requires a human touch."

Her observation emphasizes the exploratory nature of AI in science. It's not just about automating existing processes, but also discovering new ways to approach and understand astronomical data.

Looking to the future, AI is expected to be at the forefront of astronomy and, eventually, other aspects of space exploration. From autonomous spacecraft navigation to real-time data analysis, it will play a pivotal role in future missions, potentially even in the search for life beyond Earth.

More immediately, the continued advancement of AI in astronomy holds the promise of new discoveries. As AI becomes more sophisticated, its ability to uncover fainter, more distant exoplanets will continue to grow, potentially revealing planets that were previously beyond observational reach. However, some researchers have concerns.

Pennsylvania State University astronomer and distinguished professor Eric Ford points to the current focus in AI development, which often prioritizes prediction over interpretability. "There's a lot of interest in methods that make predictions ... but there's not as much emphasis on accuracy and on interpretability and explainability."

In science, understanding and explaining evidence is equally, if not more, important than making predictions. Ford's vision is one where the technology not only aids in discovery but also enhances humanity's understanding of the universe. His perspective extends beyond the technical aspects of AI, venturing into its societal and ethical implications. Ford worries about a future where AI accelerates the pace of research to the point where quantity overshadows quality, and he advocates for a responsible approach to AI in which human oversight is central to the validation of scientific discoveries.

"There's a lot of work to be done, and not just for astronomy," he explains. "We want to understand why AI algorithms make a certain prediction so we can critique it and decide whether we are comfortable acting on its predictions."

This statement underscores the broader impact of AI in various fields and the importance of maintaining a critical approach towards its outcomes. Ford sees astronomy as a field that can model responsible AI use. Since the field is driven by curiosity rather than economics, it allows for a more objective approach to scientific research. "One of the benefits of astronomy is our data have no monetary value," he notes. "We're willing to share data with you; we're willing to make our entire pipeline public, so it can be scrutinized and improved."

Overall, artificial intelligence's astronomical role isn't just as a tool that replaces human effort, but also as an evolving partner that reshapes how astronomers work and what they can discover. AI and machine learning aren't just enhancing the efficiency of data analysis in astronomy, but are also enabling new discoveries and allowing astronomers to engage more deeply with the most intriguing aspects of their research. As AI continues to evolve, its impact on astronomy and our understanding of the cosmos is likely to grow even more profound.

"Machine learning is revolutionizing how we find exoplanets," Christensen said. "It's like having a highly efficient assistant that never tires, continuously analyzing data for potential discoveries. We're still exploring the best ways to use machine learning in astronomy. It's a tool that's continually improving our understanding of the cosmos." ■