Exploring strange new worlds with high-dispersion spectroscopy

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Summary

Throughout history, humanity has been fascinated with the Universe. We have continuously sought to expand our understanding of its many wonders and, by extension, our place in it. Perhaps unsurprisingly, the existence of worlds beyond Earth has proven a recurring topic in philosophy and science fiction for millennia. Only about thirty years ago, however, did alien worlds fully enter the domain of science with the discovery in 1995 of a planet orbiting a star other than the Sun. In the decades since, much progress has been made to better understand these so-called exoplanets. As of the publication of this dissertation, approximately 5000 planets outside the Solar System are known to exist, and it is believed that there are at least as many planets in our Galaxy as stars. Such plenty brings with it the exciting opportunity to explore these strange new worlds and begin to answer questions such as *What kinds of planets exist beyond the Solar System? Of what are these planets made? How did they form?* and *Is there life beyond Earth?*

The methods used to detect exoplanets often provide very basic information about their characteristics, such as physical size and mass — the amount of composing material. With this information, it is possible to determine how dense a given exoplanet is, and thus infer whether it is made of mostly rock, ice, or gas. In this way, it is possible to develop a basic understanding of what kinds of exoplanets exist in our Galaxy. However, to understand planets beyond the Solar System in more detail, it is necessary to comprehensively study their atmospheres. Only then is it truly feasible to answer the aforementioned fundamental questions of exoplanetary science.

To study the atmospheres of exoplanets, it is common to perform spectroscopic observations — that is, to observe these objects using different colors (wavelengths) of light. In the resulting spectrum of a planet's atmosphere is encoded a wealth of information about its chemical composition. Different chemicals have unique spectral fingerprints in that they absorb and emit light of

different colors in a unique way. These unique patterns allow different chemicals to be distinguished from one another. Their presence or absence in the spectrum of an exoplanetary atmosphere thereby probes the chemical composition of these objects, despite them being trillions of kilometers away from Earth. Using high-dispersion instruments that more finely distinguish different wavelengths of light enables more robust analyses of atmospheres. Chapters 2–5 of this dissertation present four research projects studying exoplanet atmospheres at high dispersion.

Chapter 2 details a study to understand the chemical composition of some of the most extreme exoplanets. Hot Jupiters are gas-giant planets that orbit their stars at very close distances. A "year" on such planets lasts only a few days. For comparison, Mercury — the closest-orbiting planet in the Solar System — passes around the Sun in about 90 days. When these extreme exoplanets were discovered in the 1990s, research began to better understand the nature of their atmospheres, and in particular, the effect of receiving such an intense amount of starlight. It was predicted that these exoplanets orbit so closely to their stars, and thus their atmospheres are so hot, that the molecule titanium oxide (TiO), composed of a single atom each of titanium and oxygen, should exist as a gas at high altitudes on these worlds. However, studies that set out to test this theory have largely failed to provide unambiguous evidence for TiO gas in these hot, closely-orbiting gas-giant planets. The work presented in this chapter tried to reproduce a seminal detection of TiO in a particular planet called WASP-33b. At the time, it was the only unambiguous discovery of the molecule in such a planet. However, despite using the same observations and a better "fingerprint" for this chemical, we could not confirm its presence in WASP-33b. As discussed in Chapter 2, this conclusion serves as a cautionary tale regarding the techniques we use to study exoplanet atmospheres at high dispersion, and weakens the once seminal detection of TiO in this particular planet. In turn, the ambiguity surrounding the presence of TiO in these hot exoplanet atmospheres remains.

Chapter 3 investigates the feasibility of studying the different isotopes of titanium in large gaseous exoplanets. Isotopes are different varieties of a given chemical element, and behave slightly differently from one another. Measuring the comparative amount of each isotope of a chemical can provide information about an object. For instance, studying titanium isotopes in stars has provided information about the evolution of our Galaxy, whereas similar studies in the Solar System have been used to study its formation. In future, such analyses may provide similar insight into the formation of exoplanets. We first checked whether the analysis techniques commonly used to study exoplanet atmospheres provide accurate measurements of titanium isotopes. We did this by applying these exoplanet-specific techniques to observations of a star, known to have TiO in its atmosphere composed of the different isotopes of titanium. By comparing our results to those from previous studies of similar stars, we conclude the methods used to study exoplanets should not significantly affect what we measure for the quantities of titanium isotopes. With this assurance, we determined how much observing time on current and future telescopes is required to perform such a study on a fainter exoplanet. Excitingly, studying titanium isotopes in large, widely-orbiting gas-giant planets is very feasible with current and upcoming observatories.

Chapter 4 presents an attempt to detect young, still-forming planets in an effort to better understand how this process works. Young stars are surrounded by so-called protoplanetary disks composed of gas and dust, in which it is believed planets form. Indeed, structures like rings, gaps between rings, and spirals are often seen in these protoplanetary disks, and are thought to be caused by young, possibly still-forming, planets. Studying the atmospheres of nascent planets is the most straightforward way to understand the planet-formation process, rather than trying to infer the history of an exoplanet after the fact. However, finding such young objects is rare. Recently, a study was published on the young star system HD 169142 suggesting a young planet may be present and causing the rings and spiral structures observed in that system's protoplanetary disk. We searched for, but could not find, evidence of this young planet's atmosphere in different observations of this system. We determined the data we used for this analysis is, in fact, not sensitive enough to detect the proposed planet, and thus more observations are required to confirm or deny its presence.

Chapter 5 concludes this dissertation with a forward-looking project evaluating the ability of large future telescopes to detect molecular oxygen (O_2) in Earth-like exoplanets. Just like on Earth, it is expected that O_2 may trace the presence of life on rocky exoplanets. There are, naturally, intricacies to this relatively simple relation, and many other criteria must be fulfilled before we can declare any future detection of oxygen to be evidence of extraterrestrial life. Nonetheless, the search for such biosignatures — chemicals that are associated with life on Earth — in the atmospheres of other worlds is seen as the most reasonable way forward in the search for life beyond the Solar System. Our work builds on previous studies which looked into the feasibility of using the upcoming larger and more powerful "extremely large telescopes" to search for O_2 in rocky exoplanets similar to Earth. Specifically, we performed our study in a manner that more realistically represents future searches for O_2 in Earth-like planets. We find that these more accurate simulations give very similar predictions for how difficult it will be to detect O_2, and that even using these newer and more powerful telescopes, it will take several years to collect the necessary observations for a single exoplanet.