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VOYAGERS ***Views Of Yore — Ancient***

Gaia-enceladus Exoplanet Revealing Survey

Discovery of Giant Exoplanet Candidates Orbiting Ancient Stars Born Outside the Milky Way Galaxy

By

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Melinda Soares-Furtado, Assistant Professor, Physics
Thomas Beatty, Assistant Professor, Astronomy
Juliette Becker, Assistant Professor, Astronomy
Ke Zhang, Assistant Professor, Astronomy

Chapter 1

Thesis Summary for a Broader Audience

Thesis Title: ***VOYAGERS Views Of Yore — Ancient Gaia-enceladus Exoplanet Revealing Survey: Discovery of Giant Exoplanet Candidates Orbiting Ancient Stars Born Outside the Milky Way Galaxy***

Who am I? Why should you read this 100+ page thesis?

Lucky for you, you can read this brief summary to get a quick idea of what is inside. First let me introduce myself. I am Bob Aloisi, a non-traditional student, 61 years old, and still studying. I spent 29 years developing new products in the paper and non-wovens industries in Wisconsin before I returned to school at UW–Madison to pursue my passion for astronomy. I am a life-long learner, earning all my post-secondary degrees at Wisconsin institutions, with 4 degrees from UW–Madison: a bachelor's degree in chemical engineering and a Master's in engineering management (both earned a long time ago), and now a Master's and a PhD in astronomy (this thesis). I have always been fascinated by exoplanets — planets that orbit stars other than the Sun. Over 6000 exoplanets have been discovered that orbit stars in our Galaxy, the Milky Way.

What is this thesis about?

This thesis describes early results from the VOYAGERS survey, which is a search for exoplanets orbiting stars that were born outside the Milky Way in a dwarf galaxy called Enceladus. Enceladus merged with the Milky Way early in the life of the Universe, about 10 billion years ago. My project searched 22 stars that are near the Sun that are part of a stream of stars left over from the dwarf galaxy, which is called Gaia-Enceladus-Sausage (GES). We know that these stars all formed early in the Universe because the merger event stripped all the interstellar gas from GES, leaving no cold gas from which new stars would form. These stars are very different from the Sun because they are so old. At that time in the Universe, there were fewer heavy elements like iron (Fe) that form inside stars. These heavy elements are blasted into interstellar space when massive stars explode in supernovae. Later generations of stars incorporate the heavy elements seeded by the supernovae. Astronomers call these heavy elements metals and therefore more recently formed stars like the Sun, which formed about 4.5 billion years ago, have higher metallicity, which is the ratio of Fe to hydrogen (H), which is the lightest, most plentiful element.

I am working with a collaboration of astronomers from around the world, using observations from large telescopes in Arizona, on La Palma in the Canary Islands, and in central Spain to search for exoplanets orbiting ancient stars that formed in a dwarf galaxy outside the Milky Way. These telescopes have instruments called spectrographs that separate a star's light into a spectrum (brightness across a range of wavelengths, like a rainbow). High-precision spectrographs like the ones used in this survey (TRES, NEID, HARPS-N and CARMENES) can discover exoplanets by looking for a wobble in the star's motion over time, taking many careful observations, each taking 5 to 30 minutes depending on the brightness of the star. Our ongoing survey targets 100 observations per star on 22 stars over 4+ years to build up enough data to find planets with around the mass of Neptune or greater depending on how far the planet is from its star.

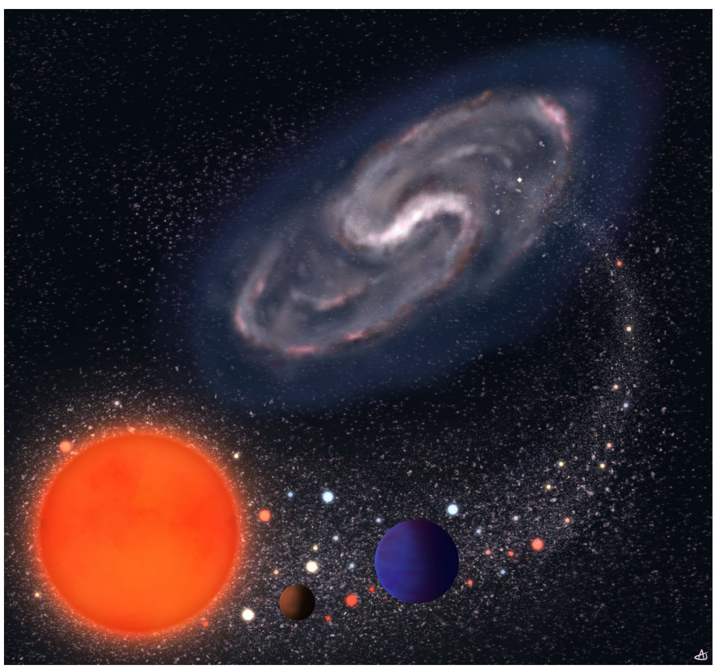

Figure 1.1: An artist's conception of a star with planets in a stream of stars falling into the Milky Way Galaxy. Credit: Alyssa Rose Jankowski

How do you find exoplanets?

This survey uses the radial velocity method, illustrated step by step in Figure 1.2. A star's spectrum is crossed by many dark lines, created where different elements at the star's surface absorb light. Each element absorbs in its own distinctive pattern, and we know exactly where those lines should fall because we can measure the same elements in laboratories here on Earth. In a star's light, though, the entire pattern appears shifted by the Doppler effect: it slides toward the blue end of the spectrum when the star is moving toward us, and toward the red end when it is moving away. The wobbles I mentioned earlier happen when a star and an orbiting companion — a massive planet, or even another star — circle each other. Each wobble is a small change in the star's speed along our line of sight (its radial velocity), and it nudges the spectral lines by tiny amounts that we can measure very precisely. Over time, we watch those lines slide back and forth in a steady, repeating rhythm, like a sine wave — and from that motion of the star, we can confirm that a planet is orbiting it. Other detection methods exist, but this is the one our survey relies on.

Have you ever wondered how long ago life could have formed around other stars?

Planets form around the same time as stars, when shocks from nearby supernovae or young massive stars allow gravity to collapse a cold cloud of dust and gas molecules into relatively dense clumps. As a clump collapses it begins to rotate, and a star forms at the center while planets form within a disk of gas and dust spinning around it. Observations have shown that stars hosting giant planets with masses similar to Jupiter tend to form from clouds richer in heavy elements, and some recent work suggests that giant planets could not form until later in the history of the Universe, once enough of these heavy elements had built up. The reason is timing: there is only a short window early in a star's life before winds from the star blow away the gas and dust available to make planets. Giant planets are thought to form by one of two main pathways, shown side by side in Figure 1.3. The first, core accretion, proposes that planets begin as dust that clumps into pebbles, which combine into ever-larger bodies until a solid core forms about ten times more massive than Earth; this core can then gather gas to produce a giant planet like Jupiter. If a core takes longer to grow heavy enough to attract gas than the disk takes to disperse, no giant planet is made—and because heavy elements speed up the growth of the core, this naturally explains why giant planets are found more often around stars rich in metals (high metallicity). The second pathway, disk instability, proposes that some giant planets form directly from the collapse of dense regions of gas in the disk. Simulations predict that planets formed this way tend to lie farther from their star and to be more massive, often near the boundary of brown dwarfs—objects more than about 13 times the mass of Jupiter. Astronomers do not count brown dwarfs as planets because they are massive enough to undergo some fusion, and stars are more massive still—massive enough to fuse hydrogen.

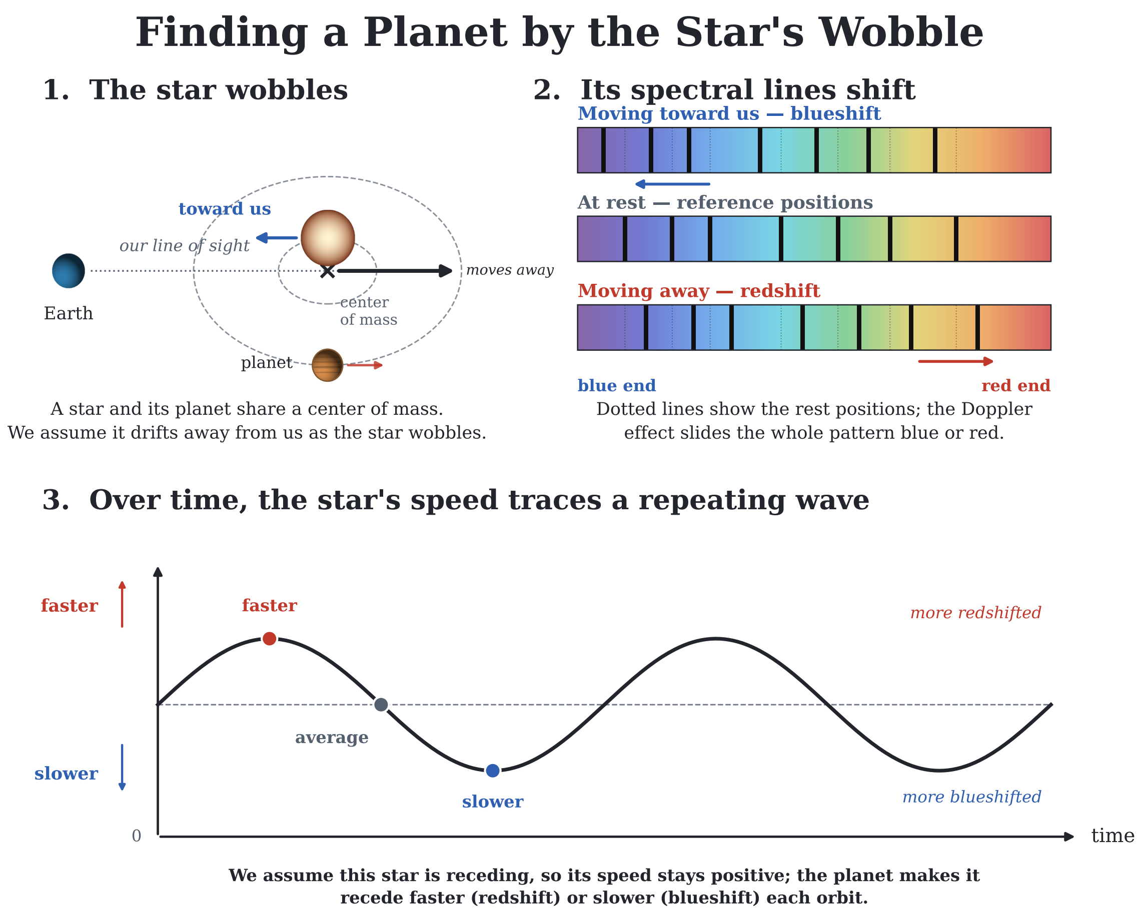

Figure 1.2: An illustration of the radial-velocity method described in the text: a star's small wobble (1) shifts its dark spectral lines toward the blue or red end of the spectrum (2), which, measured over time, traces a repeating wave in the star's speed (3) whose size reveals the orbiting planet. Credit: Bob Aloisi using Claude AI

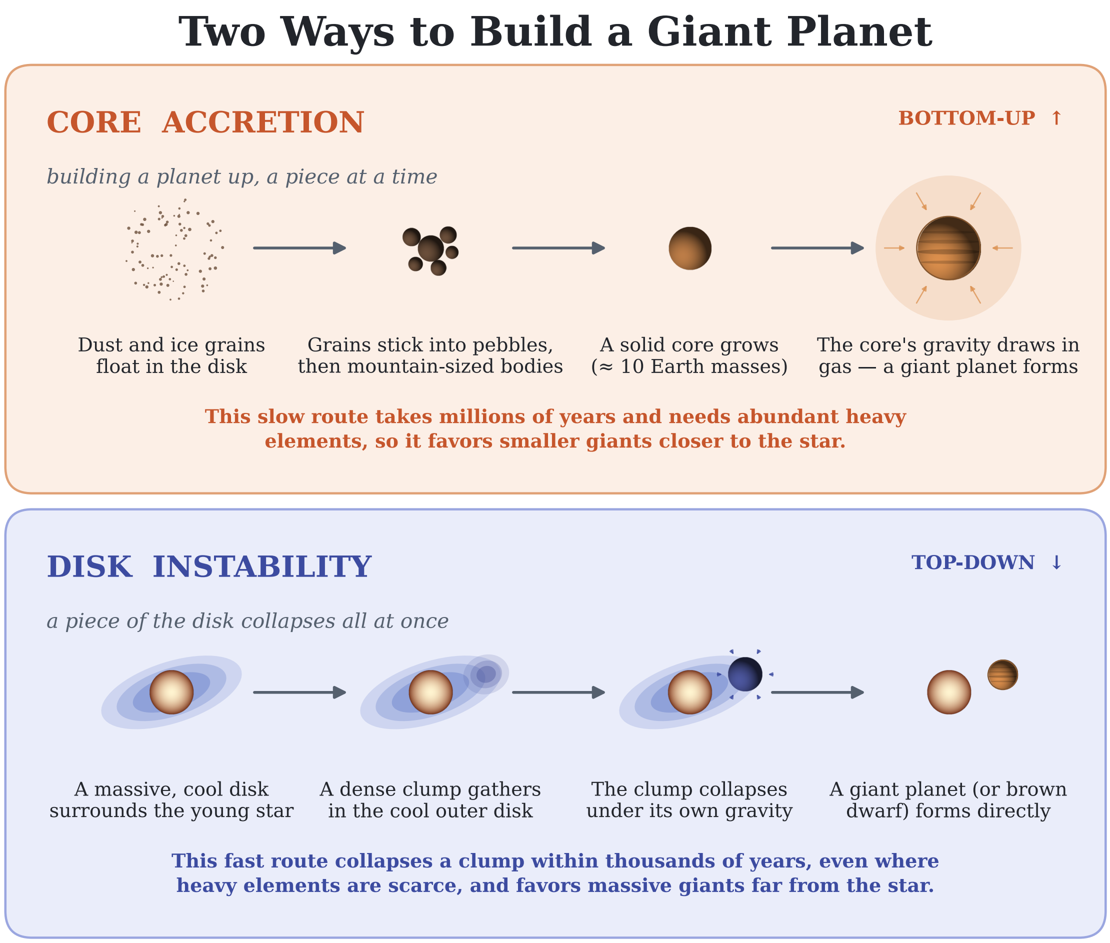

Figure 1.3: The two pathways by which giant planets are thought to form. Core accretion (top) builds a planet from the bottom up, slowly growing a solid core that then draws in gas, while disk instability (bottom) forms a giant from the top down when a clump in the cool outer disk collapses directly. As described in the text, the two routes differ in how quickly they act, in how strongly they depend on heavy elements, and in the size and location of the planets they produce. Credit: Bob Aloisi using Claude AI

Did giant planets form in the Early Universe?

Giant planet candidates were found orbiting three of the stars in the survey. One of the candidates was observed over several ∼150-day orbits, which allows the team to estimate its mass and separation from the star. Its mass is about half Jupiter's mass and it is about half as far from its star as Earth is from the Sun. I refer to this as an exoplanet candidate because more observations are needed to be confident that the signal is from a planet, not other sources like star spots rotating into view, pulsations of the star, or even interference from elements in our atmosphere absorbing some of the light. The other two candidates show long term trends that indicate something is orbiting the star, but we don't know the period or mass of the objects yet. They could be giant planets like Jupiter or they could be brown dwarfs, which are about 13 times Jupiter's mass or more. They could be even more massive stars orbiting much farther from their host stars. We will continue to observe all three candidates and publish additional papers when we are confident that planets are causing the signals. **The tentative answer is yes, based on our survey it looks like giant planets formed about 10 billion years ago as long as even one of the candidates is confirmed.**

Why are exoplanets born outside the Milky Way important?

If confirmed, any of the three candidates will be the first known exoplanet to have formed in a dwarf galaxy in an environment that is very different from our solar system. If these giant planets are confirmed, there is a good chance that planets with masses close to Earth also formed early in the Universe orbiting these types of stars. Some of these planets could be in what we call the habitable zone of their star, where liquid water can exist on the surface, like here on Earth. If so, life could have developed a long time ago and could have survived until today, a much longer time than life has existed on the Earth. Stars from dwarf galaxies that merge with the Milky Way have unusual orbits because they fell into our galaxy starting far from the center at various angles to the Milky Way disk. This could have an advantage for the long-term survival of life, because most supernovae occur in the disk of the Galaxy and there is a lower chance that these stars would have been close enough to supernovae to sterilize life.

How does your research affect society?

Understanding our place in the Universe is one of the big questions scientists are currently studying. Is Earth unique or are there other habitable planets? Is there life out there? Where are they? This thesis describes one project in which we are attempting to find answers to these questions. We have only confirmed that planets orbit other stars like the Sun (most of which formed in the Milky Way disk) in the last 30 years. This is just one project expanding the search for planets. If we find planets around these stars that spend most of their time outside the disk, they will be excellent candidates for organizations like the Search for Extraterrestrial Intelligence (SETI) to search for signals from intelligent life. It would be amazing to find out that somewhere life has found a way to survive for billions of years longer than the only place we know it exists — here on Earth.

This project is the work of a collaboration of dozens of astronomers. I'm proud to have led the VOYAGERS survey during my graduate program. Our observations would not be possible without state-of-the-art instruments built and operated by other scientists. All this work is funded through grants and proposals outlined in the thesis acknowledgments. Thank you to the Wisconsin Initiative for Science Literacy for a grant and feedback to help create this chapter. Thank you for taking the time to read this brief summary. Check out the details if you have the time.