Young suns and infant planets: probing the origins of solar systems

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Chapter 7

Outlook

The main objective of my future work will certainly be the conclusion of YSES. First and foremost, this means collecting all remaining second epoch observations for 44 stars from our sample that host unconfirmed candidate companions. As soon as these data have been collected, we can derive a meaningful occurrence rate of extra-solar giant planets to young, Sun-like stars. The new planet detections from YSES and our sensitivity limits will then be combined in a final statistical survey paper. Comparison to model predictions based on the various formation mechanisms will enable us to probe the formation pathways of giant Jovian companion to Sun-like stars, similar to Nielsen et al. (2019) and Vigan et al. (2020). Never has this problem be approached on a sample that was as homogeneous and that contained as many stars of $1\,M_{\odot}$. Therefore, our results will have vital implications for gas giant formation in solar-like environments.

Besides, each detected planetary-mass companion will foster an abundance of follow-up characterization measurements. This will allow to test the framework proposed by Öberg et al. (2011) on a large and statistical significant sample of giant companions for the first time. We will begin to systematically probe molecular abundance ratios in exoplanet atmospheres, enabling analyses as to whether this quantity is indeed a reliable tracer of planetary birthplaces. Additional isotopologue measurements might be helpful to support hypotheses based on molecular abundance ratios alone. Especially VLT/CRIRES^{+}, VLT/ERIS, VLTI/GRAVITY, and JWST will play crucial roles in obtaining these measurements.

Future direct imaging surveys (perhaps inspired by the YSES approach and strategy) will certainly continue to expand the sample of gas giant wide-orbit planets. A potential successor program of YSES could be designed as described in the following section.

7.1 LEGACYS: The Large Extrasolar Giant planet Abundance Census around Young Suns

By construction, the YSES sample is representing only a short time frame of the pre-main-sequence evolution of planetary systems. To test several formation scenarios of early, solar-like environments, the logical next step is to extend the sample towards the temporal dimension without altering the previously fixed constraint on the host star masses. Planet occurrence rates and semi-major axis evolution as a function of

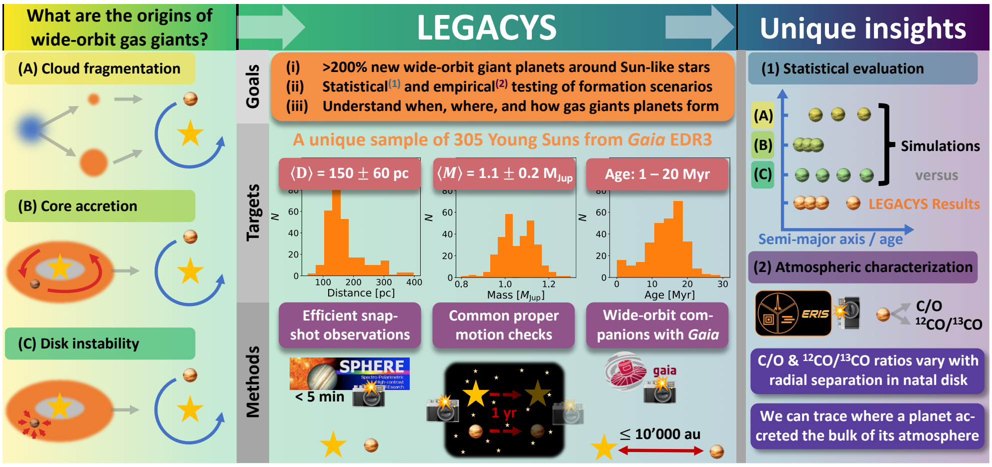

Figure 7.1: Schematic overview of the LEGACYS project.

stellar age are great tracers of different formation scenarios: scenario (B) — in which the planets form close to the host star and migrate outwards driven by scattering processes — imposes a positive correlation of planet separations and increasing system ages, whereas a flat distribution of semi-major axes versus time is expected for the in-situ formation mechanisms (A,C).

LEGACYS aims to shed light on the enigmatic origins of wide-orbit gas-giant planets in young solar systems by observing a homogeneous sample of 305 solar-mass pre-main sequence stars to detect and characterize wide-orbit companions to these young, solar analogs (see Figure 7.1). This survey will

(i) more than triple the small sample size of directly imaged gas-giant planets to Sun-like hosts to

(ii) facilitate statistical analyses regarding the occurrence rates of these objects as a function of time without diluting effects due to varying host star masses (see Chapter 1.3.1) and to

(iii) enable atmospheric characterization of a significant sample of wide-orbit Jovian companions (see Chapter 1.3.2),

(iv) and thus, foster accurate testing of different formation scenarios by exploring the full spatial, temporal, and chemical parameter space of our sample for the first time (right panel of Figure 7.1).

The survey strategy is summarized in the carton presented in Figure 7.1. It relies on an unbiased sample of young, solar-type stars with various ages, compiled from the pre-main sequence star catalog compiled by Zari et al. (2018). These targets are members of various young associations representing different ages of early pre-main sequence evolution: Scorpius-Centaurus – with its sub-groups Upper Scorpius (10 ± 3 Myr), Upper Centaurus Lupus (16 ± 2 Myr), and LCC (15 ± 3 Myr) – Lupus ($1 - 3$ Myr), Taurus (~ 1 Myr), and Corona Australis ($1 - 3$ Myr). As presented in Figure 7.2, the LEGACYS sample comprises the closest and largest selection of young, solar-mass stars to our Sun, complementary to the parameter space probed by other

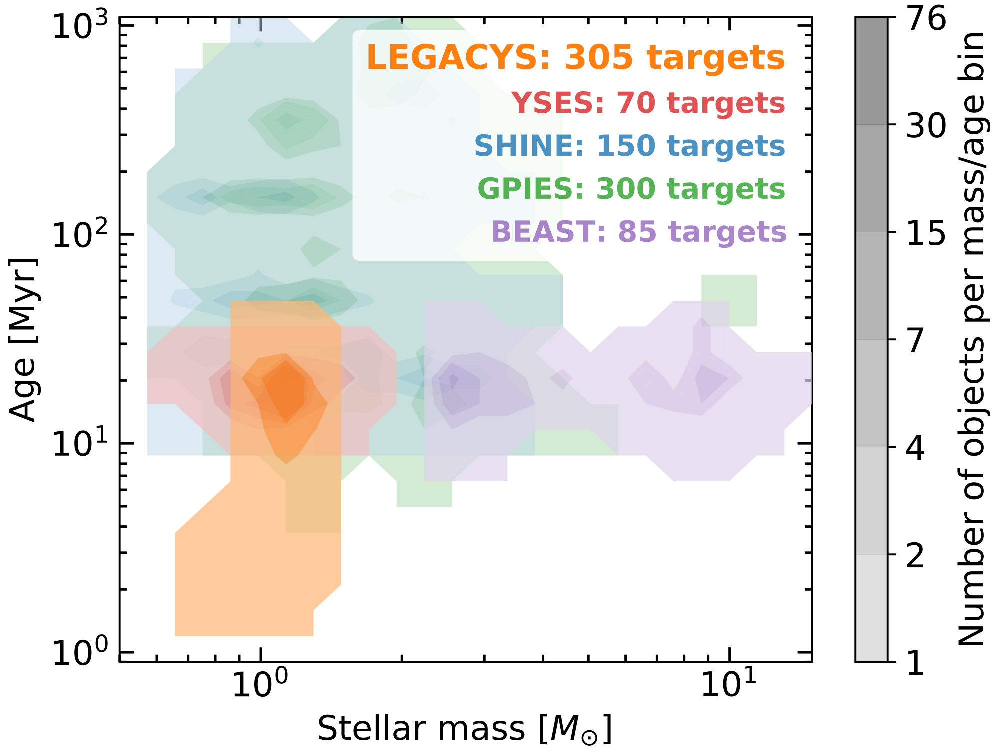

Figure 7.2: Comparison of the LEGACYS sample to previous direct imaging surveys. LEGACYS is expanding the YSES sample towards the temporal dimension and targeting the largest selection of young, Sun-like stars amongst all surveys. For each survey, the different shades of color represent the number densities of target stars in this mass-age diagram.

direct imaging campaigns. These targets can be observed in a similar snapshot approach as applied for YSES; data reduction would be performed by RDI with an even larger reference library of similar targets. With an abundance of new detections of wide-orbit, planetary-mass companions, this new survey will have an unparalleled legacy value and will provide a temporally-resolved insight into the initial stages of planetary systems for the first time. Studying the entire pre-main-sequence evolution of solar-like environments and comparing the observed occurrence rates to simulated planet populations will provide vital implications for the efficiency of the underlying planet formation mechanisms. YSES and perhaps LEGACYS will be crucial to constrain the underlying formation pathways of wide-orbit Jovian gas giants to solar-type host stars, and these surveys will perfectly complement the results of other large programs such as SHINE, GPIES, and BEAST.

7.2 Our place in the Universe

The observations of the past years have shown that planetary systems are ubiquitous with various architectures either similar or vastly different from our Solar System. Based on this plethora of exoplanets, it is likely that one of these worlds will exhibit favorable conditions to develop something that can be considered as *life*. As humanity has learned to accept their own mediocrity throughout the past centuries, it would not be surprising if we learned one day that there is life outside of Earth. Recent estimates of $\eta_\oplus$ – defined as the occurrence rate of Earth-sized rocky planets that reside in the habitable zones of their host star – can be quite inconsistent and vary from $\eta_\oplus = 0.064$ (Silburt et al. 2015) to $\eta_\oplus = 0.35$ (Barbato et al. 2018). Yet they are usually significantly larger than zero. Even if the probability that an individual terrestrial planet in the habitable zone facilitates favorable conditions for life to emerge is tiny, this small likelihood should be compensated by the huge number of stars in the Universe.

Of course, this does not necessarily mean that this extraterrestrial life will actually be located in our Galactic neighborhood; and even if it is, it is still unclear if we will be able to actually detect it. However, the recent progress in exoplanetary sciences provided promising results, and especially future observatories such as the ELTs, LUVOIR, HabEx, and LIFE will play a crucial part in finding an answer to this most ancient question of humankind.