Using Solar Twins to Explore the Planet–Star Connection with Unparallelled Precision

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This year marks the 20th anniversary of the first definitive detection of an exoplanet orbiting a Sun-like star by Mayor and Queloz (1995). Almost 2000 exoplanets have been discovered since this breakthrough, but many fundamental questions remain open despite the enormous progress: How common are analogues of the Solar System? How do planets form and evolve? What is the relationship between stars and planets? We are observing stars that are near-perfect matches to the Sun to provide new insights into the above questions, thus exploring the planet–star connection with unprecedented precision.

The relationship between stars and planets

Stars and planets are formed from the same natal cloud and the two processes occur on similar timescales, and thus a natural connection between stars and planets is expected to arise at these early stages. The formation of rocky planets requires refractory elements, i.e., those that condense at high temperatures (about 1500 K), which are found in the inner protoplanetary disc. In contrast, giant planets are rich in volatile elements that can condense only at low temperatures (< 200 K) and are found in the outer region of the proto-Solar nebula. As the process of planet formation and the last stages of star formation are coeval, chemical signatures of planet formation can be imprinted on the outer zones of stars, because the late-accreted gas could be depleted in some chemical elements by the sequestration of the different chemical elements needed to form planets.

The most-studied signature of a relation between stars and planets is the higher frequency of close-in giant planets around metal-rich stars (Gonzalez, 1997). Stars with metallicities higher than the Sun are observed to have a higher chance of hosting a close-in giant planet, reflecting the trend that giant planet formation is enhanced in discs of higher metallicity. Planet engulfment events can also enhance the stellar metallicity, as predicted, for example, by Laughlin & Adams (1997) and probably observed in one star of the γ Velorum cluster by Spina et al. (2014). Iron is used as a proxy for stellar metallicity because it has many lines in the spectra of Solar-type stars, and it is thus easier to estimate its content. About a decade after the discovery of the correlation between giant-planet frequency and iron abundance, it was suggested from observational studies that there is no significant correlation between Neptune-mass planets and the iron abundance of the host star (e.g., Sousa et al., 2008; Ghezzi et al., 2010).

For more than a decade after the landmark discovery by Gonzalez (1997), no other firm relations are known for elements other than iron. This is because the most optimistic minimum uncertainties in chemical abundance analyses are 0.05 dex (Asplund, 2005), which are too high to convincingly detect the effect of rocky planets such as the Earth (predicted to be only a few times 0.01 dex). Our group was the first to achieve the requisite milestone 0.01 dex precision (Melendez et al., 2009), by performing a strictly differential analysis between Solar twins and the Sun, opening new windows on the study of the planet–star connection.

Solar twins and planet signatures

Solar twins are stars with physical characteristics (effective temperature, surface gravity and chemical composition) similar to the Sun. With stellar atmospheres so similar to the Sun, many systematic effects that plague chemical abundance analyses are removed when each spectral line is analysed differentially between the Solar twin and the Sun, allowing a precision of 0.01 dex to be achieved. Our precision has been tested by performing differential abundances in the Sun using two different asteroids (Bedell et al., 2014), achieving an element-to-element scatter of only 0.006 dex (Figure 1). We have also studied Solar abundances at different Solar latitudes, achieving an agreement of 0.005 dex for all elements, and 0.002 dex for the refractory elements (Kiselman et al., 2011).

Our improved 0.01 dex precision led to a breakthrough in 2009, when we showed that the chemical composition of the Sun is anomalous when compared to the average composition of Solar twins. The Sun appears to be deficient in elements that are abundant in the Earth and other rocky material in the Solar System (Meléndez et al., 2009; Ramírez et al., 2009). Importantly, there is a robust correlation between the abundance anomalies and the dust condensation temperature in the proto-Solar nebula (see Figure 2). This strongly suggests a relationship with the formation of terrestrial planets in the Solar System, as verified quantitatively by Chambers (2010), who showed that the deficiency of refractory elements in the Sun could be eradicated by adding back a few Earth masses of rocky material with the abundance pattern of the Earth and meteorites.

Other recent work by our group used the binary pair of Solar twins 16 Cyg to search for signatures left over from giant planet formation (Ramírez et al., 2011; Tucci Maia et al., 2014). The secondary

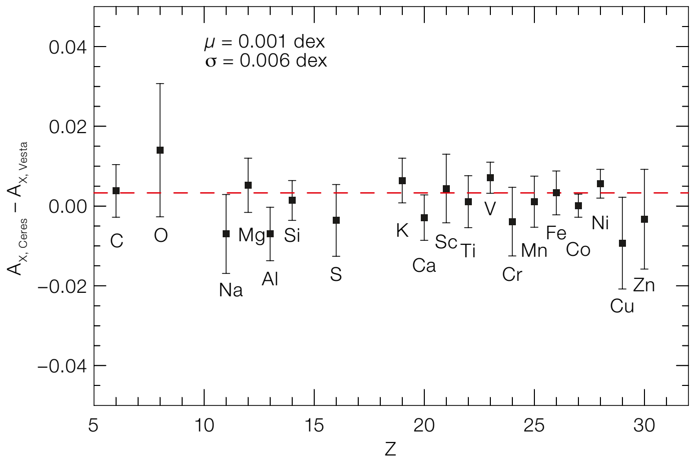

Figure 1. Chemical abundance differences between the Solar abundances obtained through reflected light off the asteroids Ceres and Vesta (Bedell et al., 2014), show an element-to-element scatter of only 0.006 dex.

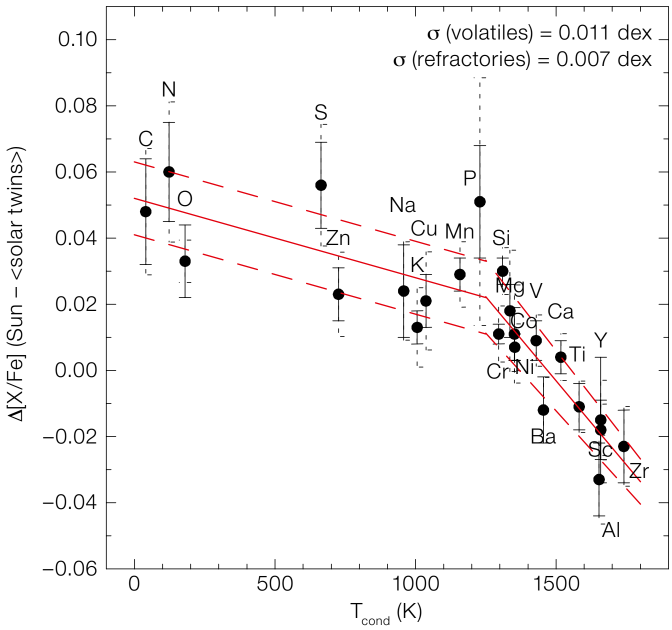

Figure 2. Chemical abundance differences between the Sun and the average of 11 Solar twins (Meléndez et al., 2009). The refractory elements in the Sun are deficient compared to the volatile elements, perhaps due to the formation of the rocky planets in the Solar System.

star (16 Cyg B) has a giant planet, while no planet has been found around the primary star (16 Cyg A). Naïvely both stars should have the same chemical composition, as they were born from the same natal cloud; however, the stars have a distinct chemical composition, with the star hosting the giant planet being more deficient in both volatile and refractory elements, perhaps because they were used to form the giant planet. A trend with condensation temperature has been suggested (Tucci Maia et al., 2014), and it could be the signature of a rocky core in the giant planet (see Figure 3). Abundance differences have been also found in the binary pair of stellar twins XO-2, where both stars in the pair host planets, providing important clues about planet formation (Ramírez et al., 2015; Teske et al., 2015; Biazzo et al., 2015).

Searching for planets around Solar twins

The synergy between accurate (0.01 dex) chemical composition determination that can be achieved in Solar twins and precise (1 m s^{-1}) radial velocities to characterise planets around these stars, allows us to study the planet–star connection at an unprecedented level of detail. Furthermore, the use of the Sun as a standard is a key part of our project, as the Sun is the only known star that hosts a planet where life thrives. In order to exploit these advantages, in 2011, we started a four-year Large Programme (188.C-0265) to use the High Accuracy Radial velocity Planetary Searcher (HARPS) to search for planets around Solar twins. We also acquired high-resolution, high signal-to-noise (S/N) spectra at the 6.5-metre Magellan Telescope to determine the stellar parameters and precise chemical composition of our sample Solar twins.

The HARPS observations are taken with a total integration time of about 15 minutes, so that oscillations from the stars are averaged to below 1 m s^{-1}. Detailed

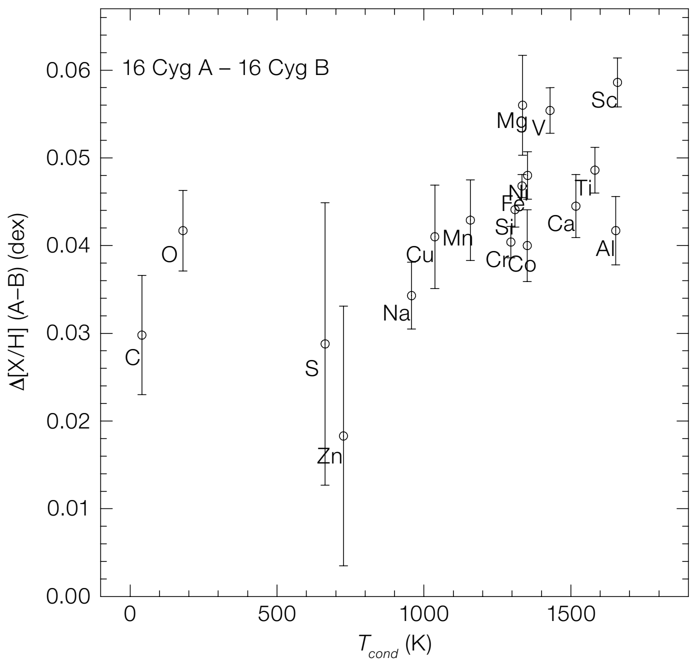

Figure 3. Abundance differences between the binary Solar twins 16 Cyg A and 16 Cyg B. The star without planets is enhanced in both volatiles and refractories, i.e., the star with a detected giant planet (16 Cyg B) is deficient in those elements, probably because they were used to form the giant planet 16 Cyg Bb. The trend with condensation temperature (T_{cond}) could be a signature of the rocky core of the giant planet.

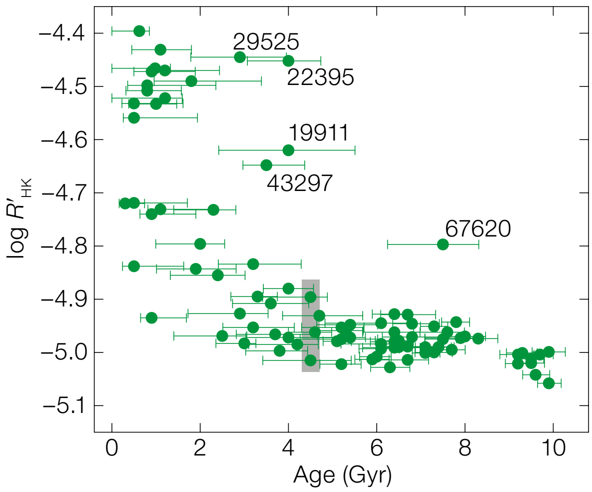

Figure 4. Evolution of stellar activity (as characterised by the R'_{HK} index, measured from the ionised calcium H and K lines) as a function of stellar age in our sample of Solar twins (Ramírez et al., 2014), showing a clear decline of stellar activity (R'_{HK}) with increasing ages. The grey bar represents the variation of the Sun's activity during its 11-year cycle; outlier stars are labelled by HIP (Hipparcos catalogue) number.

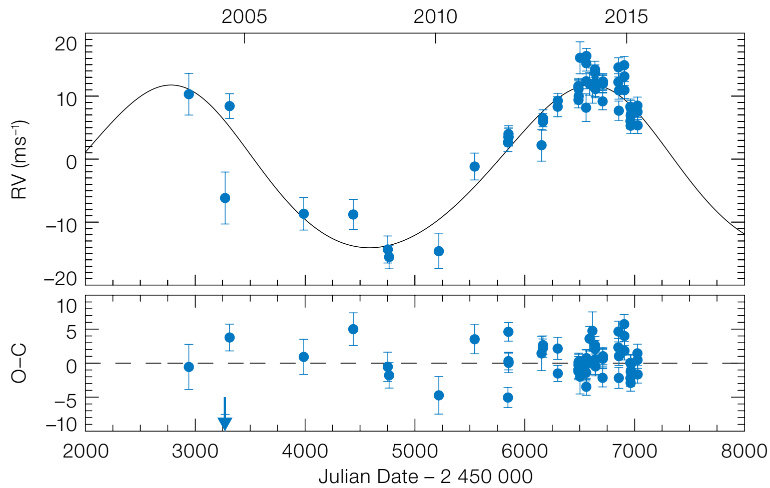

Figure 5. Radial velocity curve after subtracting the effects of stellar activity for the Solar twin HIP 11915 (Bedell et al., 2015). The data indicates a Jupiter twin, meaning a Jupiter-mass planet at about the same star–planet distance that Jupiter is from the Sun, i.e., about five times the Earth–Sun distance.

modelling of stellar activity is carried out on our HARPS dataset, because activity can induce radial velocity variations that could mimic the effect of planets. Different tests are performed to verify whether the signatures are due to planets or to other effects.

First scientific results

We have already characterised the stellar parameters and stellar activity of our sample of Solar twins (Ramírez et al., 2014), showing that they encompass ages covering the whole main sequence of a star like the Sun (a one-Solar-mass Solar-metallicity star). The sample of Solar twins can be used to study age effects on planets, stellar activity (see Figure 4), stellar rotation, stellar nucleosynthesis and the influence on galactic chemical evolution (e.g., Meléndez et al., 2014; Nissen, 2015).

Our HARPS observations have imposed stringent upper limits on the presence of planets in some Solar twins (Monroe et al., 2013; Meléndez et al., 2014), and revealed several planet candidates. Our first published planet (Bedell et al., 2015) is a Jupiter twin around the Solar twin HIP 11915 (see Figures 5 and 6). The planet has the same mass as Jupiter (within the errors) and it is located at 4.8 astronomical units (au) from its host star, quite similar to the Sun–Jupiter distance (5.2 au). According to current theories (e.g., Walsh et al., 2011; Batygin & Laughlin, 2015, Izidoro et al., 2015), Jupiter may have played a key role in the configuration of the Solar System, with stable small rocky planets in the inner region and stable giant planets in the outer region. The existence of a Jupiter twin around the Solar twin HIP 11915 opens up the possibility of a similarly stable planetary system occurring around HIP 11915. Furthermore, the abundance pattern of this Solar twin is similar to the Sun, as it is also deficient in refractory elements, and therefore enhances the chances of rocky planets being present in that system (Melendez et al., in prep.).

We are currently working on the characterisation of new planets from our sample of Solar twins. Some of the radial velocity curves for the planet candidates from our programme are shown in Figure 7. We are also working on the chemical composition of the sample of stars, to study the refractory and volatile elements (Bedell et al., in prep), and other elements, like lithium (e.g., Monroe et al., 2013; Carlos et al., in prep) and beryllium (e.g., Tucci Maia et al., 2015), that are important probes of stellar evolution.

Outreach impact

Communicating astronomy to the public is an important aspect of our programme. The far-reaching results of our project have appeared in many different countries, including different media targeting the general public (newspapers, radio, TV, internet), and also magazines specialising in science such as *Sky & Telescope, Astronomy*, and others. Our most recent discovery of a Jupiter twin around a Solar twin even had a live appearance on the most-watched TV station in Brazil (Globo), and many interviews in the national and international media were given relating to this discovery.

We have also had two ESO press releases related to our programme[1,2], and both have received wide national and international coverage, being among the most successful releases issued by ESO. One of the releases included a press conference at the Universidade de São Paulo, with live transmission.

Future prospects

Although our programme has been affected by bad weather (about one third of the time was lost), clear signatures of planets have been revealed in several of our Solar twin stars. As we approach the end of our programme, we are finalising our list of planet discoveries. The

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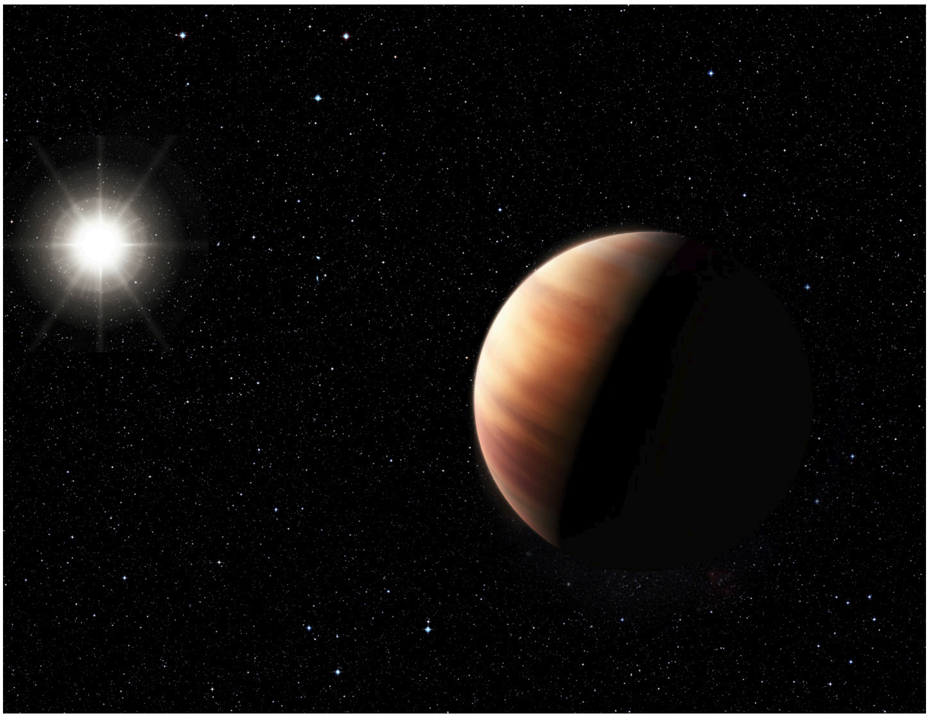

Figure 6. Artist's impression of the Jupiter twin around the Solar twin HIP 11915 from the press release.

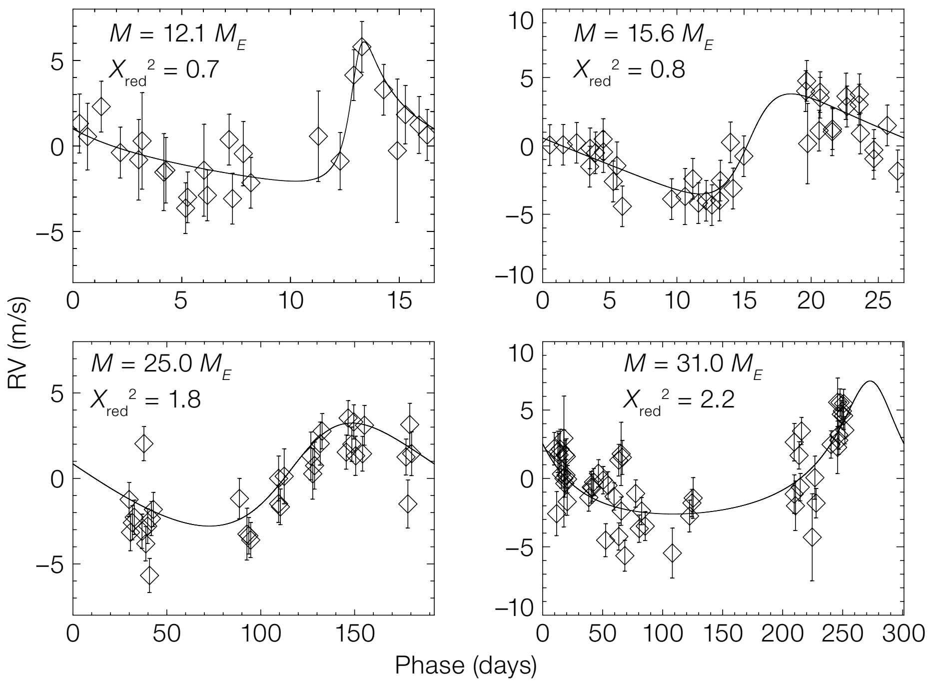

Figure 7. Radial velocity curves of planet candidates to be published from our HARPS programme. The derived mass (in Earth masses, M_E) and the reduced X^2 is shown on each plot.

planets we find with HARPS, together with the precise abundances for our sample stars, will shed new light on the connection between stars and planets, and on how unique the Solar System is.

Acknowledgements

Our Brazilian-led planet search programme is made possible thanks to the agreement signed between ESO and Brazil in December 2010, aiming to make Brazil a Member State of ESO (as recently ratified by the Brazilian Congress). After the agreement was signed in late 2010, Brazilian astronomers were allowed to apply for observing time at all ESO facilities, and in 2011, our project was approved as the first Brazilian-led ESO Large Programme. We are grateful to all the people involved in making Brazil an ESO Member State. We are also grateful to all scientists and engineers who made HARPS possible. We acknowledge funding by FAPESP and the National Science Foundation.

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Links

[1] Jupiter twin discovered around Solar twin: http://www.eso.org/public/news/eso1529/
[2] Oldest Solar twin identified: http://www.eso.org/public/news/eso1337/