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Memorie della

Global Architecture of Planetary Systems (GAPS), a project for the whole Italian Community

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Abstract. The GAPS project is running since 2012 with the goal to optimize the science return of the HARPS-N instrument mounted at Telescopio Nazionale Galileo. A large number of astronomers is working together to allow the Italian community to gain an international position adequate to the HARPS-N capabilities in the exoplanetary researches. Relevant scientific results are being obtained on both the main guidelines of the collaboration, i.e., the discovery surveys and the characterization studies. The planetary system discovered around the southern component of the binary XO-2 and its characterization together with that of the system orbiting the northern component are a good example of the completeness of the topics matched by the GAPS project. The dynamics of some planetary systems are investigated by studying the Rossiter-McLaughlin effect, while host stars are characterized by means of asteroseismology and star-planet interaction.

Key words. Stars: fundamental parameters – Techniques: radial velocities – Planetary systems – Asteroseismology – stars: activity

1. Introduction

The "Global Architecture of Planetary Systems" (GAPS) project was set after a call to the Italian scientists interested in the field of exoplanetary science to share their specific knowledge. As a result, the GAPS team joins now experts in high-resolution spectroscopy, stellar activity and pulsations, crowded stellar environments, planetary systems formation, planetary dynamics, and data handling. The team currently includes 58 astronomers from twelve INAF structures and Italian universities. Scientific and technical issues are discussed within a broad Science Team who gives advise to the Project Board. R. Claudi (2012-13), I. Pagano (2013-14), and G. Micela (2014-15) were the previous Chairpersons, while A.F. Lanza is on duty since May 2015.

The long-term, infrastructural goal of the GAPS project is to optimize the science return of the HARPS-N open time, functional at gaining a prominent position of the Italian community in the international context of the exoplanetary science. The scientific goal of GAPS is to understand the architectures of planetary systems and their properties. The adopted approach includes the search for new planets (*discovery surveys*) around stars with well-defined characteristics and the investigation of the diversity of orbital and physical properties of known planetary systems (*characterization studies*), thus exploiting at best the outstanding capabilities of HARPS-N. The two approaches are complementary and both relevant to tackle the question of the architecture of the planetary systems in a comprehensive way.

2. Observations

Since August 2012 (AOT26) 236 nights have been assigned to the GAPS program (P.I. A. Sozzetti). They were subdivided among the different sub-programs on the basis of priority reasons. Up to now (January 31st, 2015) we collected a total of 4755 spectra of 273 different objects. Figure 1 shows the statistics of the observing nights. During AOT26, in October and November 2012, the red-side chip of HARPS-N had a failure and the detector was substituted. Due to this, there was a large amount of lost nights for technical reasons (64 hrs out of 141.0 hrs). Moreover, the instrument worked with only half chip in the remaining clear hours of the period (41 hrs). Just after the HARPS-N commissioning, some technical troubles also occurred, translating into relevant losses of observing time. After the solution of several minor problems, the losses due to technical reasons settled down to usual values (~2%) in the subsequent semesters.

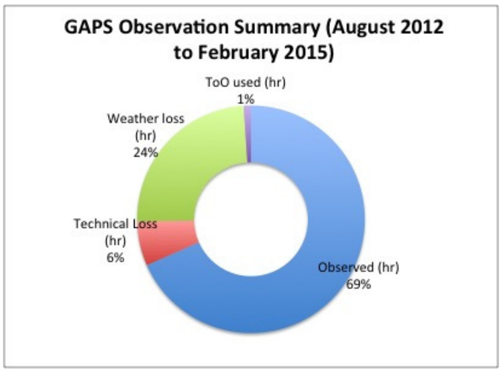

Fig. 1. The general summary of the use of GAPS observing time from AOT26 to AOT30.

The achieved radial-velocity precision depends on various factors, not the least the stellar intrinsic variability, due to pulsations and/or activity. The stellar signal is currently indicated as stellar noise or jitter, but often it contains relevant physical information, like the large separation of the solar-like oscillations or the star's rotational period. Nevertheless, even for a "quiet" star, the uncertainties on the radial-velocity value strongly depends on the number of spectral lines, as well as on their widths and depths. In order to provide a quantitative measurement of the radial-velocity precision, the quiet, non-rotating star HD166620, was observed for 21 months, from June, 2012 to March, 2014 in the framework of the HARPS-N consortium. In this case, the radial velocity dispersion was of 1.29 $\mathrm{m\,s^{-1}}$, calculated on the basis of 309 spectra taken on 21 months (Cosentino et al. 2014). This value is in agreement with the expected value and puts in evidence the high stability of HARPS-N over a long time baseline.

3. Scientific results

An important scientific return was expected from the large amount of observing time allocated at the GAPS project. This was not an obvious task when considering the high-level of competition in the exoplanetary field, the same or larger amount of time available to other

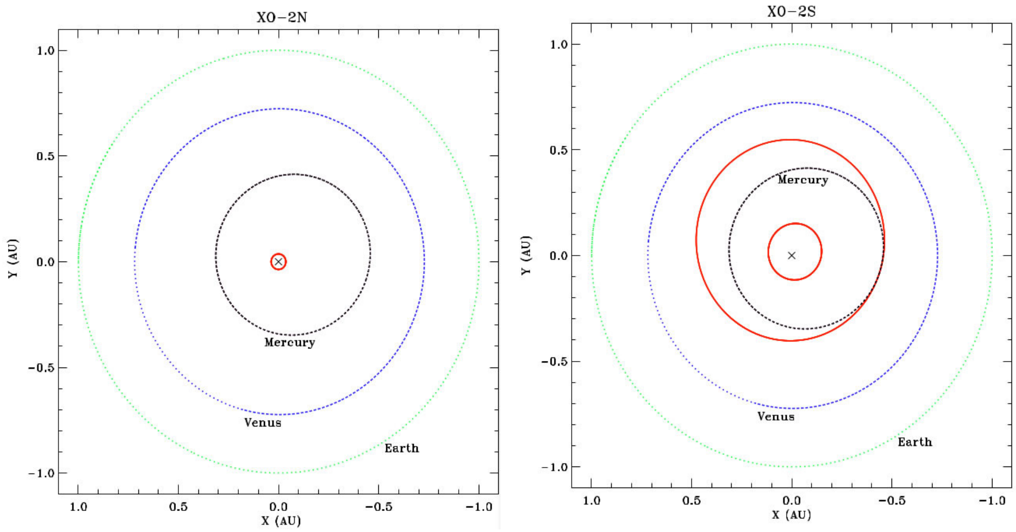

Fig. 2. Comparison of the architectures of the XO-2N (left) and XO-2S (right) planetary systems with that of the inner Solar System. Red ellipses represent the orbits of the XO-2 planets.

teams and the necessity to acquire large sets of data to detect the planetary signals in the radial velocity time series. As a consequence of this, most of the published papers are pertinent to the characterization of planetary systems rather than to the discovery of new planets. However, this should not be considered a weakness of the GAPS program. The insights into the dynamics of known systems could be more rewarding than the detection of a planet around another star, especially now that we already know more than 2000 planets. The case of the binary system XO-2 illustrates very well this point.

3.1. The two components of the XO-2 system

The formation of planets in binary systems is a challenging and interesting scientific case. Several planets orbiting one of the binary components are known. Very wide binaries are the most suitable targets to search for planetary systems around each component. We were rewarded particular attention to the XO-2 system, having projected separations of 31″ and 4000 AU. The northern component XO-2N was known to host a very close 0.5 M_J transiting planet (Fig. 2, left panel), while nothing was known about the southern one, XO-2S. Sixty-three spectra taken between April 2013 and May 2014 allowed us to discover two planets orbiting around XO-2S, and a hint of a third, long-period body (Desidera et al. 2014). Their masses are of the size of Jupiter and Saturn, in orbits wider than that of the planet around XO-2N (Fig. 2, right panel). The Rossiter-McLaughlin effect (see Sect. 3.2) was observed for the planet transiting in front of XO-2N with HARPS-N, and a detailed spectroscopic investigation pointed out the differences between the two planetary systems and an abundance of iron greater in the star XO-2N than in XO-2S (Damasso et al. 2015a). The latter fact was corroborated by a further complete abundance analysis that revealed the significance of the XO-2N abundance difference relative to XO-2S at the 2σ level for almost all elements (Biazzo et al. 2015). This result could be interpreted in two ways: *i)* XO-2N is richer in metals than XO-2S since it ingested close planets; *ii)* XO-2S has a depleted composition since heavy elements are segregated into the distant planets (Biazzo et al. 2015). The multitask approach adopted by the GAPS collaboration was very effective in investigating this binary system, whose relevance is con-

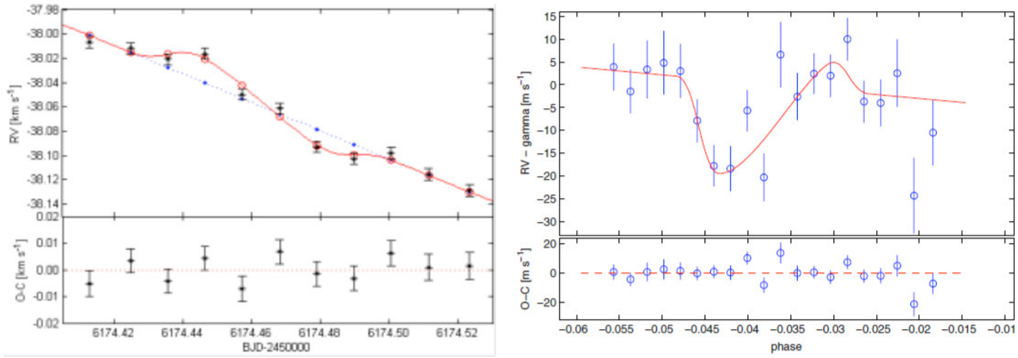

Fig. 3. The RML effects observed on Qatar-1 (left panel) and on HAT-P-18 observed with HARPS-N by the GAPS team. The opposite senses of the variations indicates that Qatar-1-b is a classical aligned system, while HAT-P-18-b is moving on a retrograde orbit. The residuals of the best-fit solutions are shown in the bottom panels.

firmed by the growing interest manifested by other groups (Ramírez et al. 2015; Teske et al. 2015).

3.2. The Rossiter-McLaughlin effect

Rossiter (1924) and McLaughlin (1924) discovered an apparent rotational effect when observing the eclipses of the β Lyr and β Per stellar systems, respectively. Nowadays this effect is thought to be a probe of exoplanet dynamical histories. It is measured using in-transit spectroscopic observations, revealing a deviation of the measured radial velocities from the Keplerian orbital motion. This apparent deviation is due to the planet occulting part of the rotating stellar surface, thus introducing an asymmetry in the profiles of the stellar absorption lines. The RM waveform allows us to determine the sky projected spin-orbit alignment angle λ between the rotation axis of the host star and the normal to the planetary orbital plane. The RM effect was recorded in the Sun due to the transit of Venus on June 6, 2012 (Molaro et al. 2013). The integrated sunlight as reflected by the Moon at night time was used to follow the transit by means of HARPS spectrograph mounted at the 3.6-m ESO telescope. The partial eclipse of the solar disc in correspondence of the passage of Venus in front of the receding hemisphere produced a modulation in the radial velocity with an amplitude of 1 $\mathrm{m\,s^{-1}}$, in agreement with the theoretical model. This detection anticipates the study of transits of Earth-size bodies in solar-type stars by means of a high-resolution spectrograph attached to a 40-m class telescope.

In the current exoplanetary researches, the alignment angle is thought to provide a window on the dynamical evolution of exoplanets. Indeed, the measurements of stellar obliquity have revealed up to now ~100 systems showing a wide range of configurations. In addition to classical aligned systems (e.g., HD 189733; Winn et al. 2006) and orbits with moderate tilts (e.g., XO-3; Hirano et al. 2011), some more intriguing cases were observed, as orbital planes that are perpendicular to the star's rotational direction (e.g., WASP-7; Albrecht et al. 2012) and retrograde systems in which the planet orbits in the opposite direction with respect to the star's rotation (e.g., WASP-17; Triaud et al. 2010). The Kozai-Lidov effect is one of the mechanisms claimed to explain such a broad variety of spin-orbit obliquities: the pertubation by an outer off-plane massive body can induce periodic oscillations in both the eccentricity and inclination of the inner planetary orbit. Inward migration of the inner planet then follows, with tidal friction driving the planet as it approaches its host, causing the orbit to shrink and circularize (Fabrycky & Tremaine 2007, and references therein).

The GAPS program includes the observation of several transiting planets showing the RM effect. Covino et al. (2013) reported about the case of Qatar-1 b, a hot Jupiter orbiting a metal-rich K-dwarf star on a nearly zero orbital obliquity (Fig. 3, left panel). The new, very precise HARPS-N observations allowed us to determine that the planet is significantly more massive than previously reported. A good sky-projected spin-orbit alignment was observed for both HAT-P-36-b and WASP-11-b≡HAT-P-10-b, too (Mancini et al. 2015). In the case of HAT-P-36, we could benefit from a coordinated intensive photometric monitoring to determine the rotational period of the star and hence not only the projected angle, but precisely the true spin-orbit obliquity. On the other hand the case of HAT-P-18-b (Esposito et al. 2014) was a very peculiar one, since the hot Saturn-mass planet orbits the late-K dwarf star with a retrograde motion (Fig. 3, right panel).

3.3. Asteroseismology of the host stars

The use of asteroseismology in the exoplanetary science is a recurrent subject in the participation of stellar astronomers to the National Conferences on Planetary Science since the launch of CoRoT (e.g., Poretti et al. 2007). The interplay between asteroseismology and planetary system evolution is one of the most innovative aspects of the ESA M4-mission Plato 2.0 (Rauer et al. 2014). This goal is pursued by the GAPS project, but the reduction of the observing time with respect to the original request did not allowed us to perform the detailed planned study. However, the bright target τ Boo A, hosting a close hot Jupiter, was monitored as a pilot study.

Despite the limited time spent on the target, the signature of solar-like oscillations was detected in the radial-velocities time series obtained with HARPS-N on τ Boo A. We could estimate the frequency of maximum power of the oscillations $\nu_{\rm max}$ and the large separation $\Delta\nu$ (Borsa et al. 2015). Both our determinations agree well with the theoretical predictions. Therefore, we could constrain the value of the stellar mass to a 4% uncertainty (1.38±0.05 $M_{\odot}$) and derive the young age of the system (0.9±0.5 Gyr).

3.4. Star-planet interaction

τ Boo A has been a very suitable target for the study of the star-planet interaction. The presence of high-latitude plage was probably detected during HARPS-N observations, while the correlation betwen the chromospheric activity and the orbital phase remains unclear (Borsa et al. 2015). We were more successful with the coordinated HARPS-N and XMM observations of HD 17156 and its planet in a highly eccentric orbit. A significant (6σ) X-ray brigthening occurred near a periastron passage of the hot Jupiter, accompanied by an increase of the Ca II H&K chromospheric index (Maggio et al. 2015).

In a parallel study to GAPS activities, Maldonado et al. (2015) calibrated some empirical relationships with the aim to determine accurate stellar parameters for M0-M4.5 dwarfs by means of the same spectra used to measure stellar radial velocities.

3.5. Solving unclear cases

One of the first results of our HARPS-N survey was the confutation of the existence of a multiple giant-planet system around the very metal-poor star HIP11952 (Desidera et al. 2013), which constituted a severe challenge for the current planet-formation models. Later, we demonstrated that the radial-velocity amplitude of TrES-4 is smaller than the previously announced one. Combined with the large radius inferred from the GAPS analysis, TrES-4b becomes the second lowest-density transiting hot-Jupiter known (Sozzetti et al. 2015).

3.6. The discovery of new planets

We already reported the discovery of two planets around XO-2S and the consequent great attention of the community around this binary system. We note that the analysis of the available radial-velocity data also pointed out possible new long-period planets around both

XO-2 components (Damasso et al. 2015a). A new, long-period planet was recently discovered around Kelt-6 (Damasso et al. 2015b). The decision to be conservative in announcing new planets, in order to report robust discoveries, is now paying since we have strong candidates for targets in open clusters (Malavolta et al., in prep.), M-dwarfs (Affer et al., in prep.) and giant stars (Micela et al., in prep.).

4. Conclusions

The scientific success of the observational program is certified by the series of papers on refereed journals (10 accepted up to now, 1 submitted, others in preparation). This compares favourably with what had been made within the first three years of operation by the HARPS@ESO GTO programme (8 published papers). But more important of this, the GAPS project has been a success in making the Italian team able to reach the critical mass required to get visibility in the international context. We also put large efforts in the Outreach and Communication activities, with regular press releases. Many of the GAPS papers have a young researcher as first author and many PhD students are being forming around the GAPS project. The GAPS visibility and school are of strategic importance when considering the preparation of future space missions devoted to the exoplanetary science as CHEOPS and Plato 2.0.

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