Evidence of a substellar companion around a very young T Tauri star

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ABSTRACT

We present results from a near-infrared multi-epoch spectroscopic campaign to detect a young low-mass companion to a T Tauri star. AS 205A is a late-type dwarf (=K5) of \( \sim 1 M_\odot \) that belongs to a triple system. Independent photometric surveys discovered that AS 205A has two distinct periods (\( P_1 = 6.78 \) and \( P_2 = 24.78 \) days) detected in the light curve that persist over several years. Period \( P_1 \) seems to be linked to the axial-rotation of the star and is caused by the presence of cool surface spots. Period \( P_2 \) is correlated with the modulation in AS 205A brightness (V) and red color (V-R), consistent with a gravitating object within the accretion disk. We here derive precise near-infrared radial velocities to investigate the origin of period \( P_2 \) which is predicted to correspond to a cool source in a Keplerian orbit with a semi-major axis of \( \sim 0.17 \) AU positioned close to the inner disk radius of 0.14 AU. The radial velocity variations of AS 205A were found to have a period of \( P \approx 24.84 \) days and a semi-amplitude of 1.529 km s\(^{-1}\). This result closely resembles the \( P_2 \) period in past photometric observations (\( P \approx 24.78 \) days). The analysis of the cross-correlation function bisector has shown no correlation with the radial velocity modulations, strongly suggesting that the period is not controlled by stellar rotation. Additional activity indicators should however be explored in future surveys. Taking this into account we found that the presence of a substellar companion is the explanation that best fits the results. We derived an orbital solution for AS 205A and found evidence of a \( m_1 \sin i = 19.25 \) M\(_{\text{Jup}}\) object in an orbit with moderate eccentricity of \( e \approx 0.34 \). If confirmed with future observations, preferably using a multiwavelength survey approach, this companion could provide interesting constraints on brown dwarf and planetary formation models.

Key words. infrared: planetary systems – stars: pre-main sequence – techniques: radial velocities – brown dwarfs – protoplanetary disks

1. Introduction

To best address the planetary formation process we should study pre-main-sequence objects (PMS) that are still enshrouded in their original environmental conditions. The age range between \( 1 \sim 5 \times 10^5 \) yr in PMSs is particularly interesting since it is the expected moment when the physical conditions in the disk enable planetesimal growth and disk migration.

In the last few years, several young planet detection surveys have been conducted in PMS stars using different techniques, such as direct imaging (e.g., Lafrenière et al. 2010; Kraus & Ireland 2012) or radial velocity (RV) monitoring (e.g., Martin et al. 2006; Setiawan et al. 2007; Crockett et al. 2012). To deploy RV surveys on young low-mass stars (which are considerably faint, distant and affected by extinction) is, in most of cases, an arduous task. This is partly due to the presence of cool spots produced by strong stellar magnetic fields (e.g., Johns-Krull 2007; Melo 2003), and to intense stellar activity which causes RV variability of PMS objects. These effects introduce high uncertainties to the RV measurements as well as relevant modulations of spectral line profiles that can mimic the presence of substellar companions (e.g., Saar & Donahue 1997; Hatzes 2002; Figueira et al. 2010a). While spectral distortions produced by cool spots are wavelength dependent (e.g., Vrba et al. 1986; Huélamo et al. 1998; Figueira et al. 2010a), RV variations caused by the presence of a low-mass companion affect all wavelengths equally. To diagnose whether RV variability is companion- or spot-induced, RVs and cross-correlation function bisector (BIS) measurements are correlated as are measures of other activity indices (e.g., Figueira et al. 2013) in order to search for activity induced trends (see Sect. 4.2).

In the near-infrared (NIR), the effect of stellar spots is expected to be considerably weakened when compared to the optical domain (however, see Reiners et al. 2013). Furthermore, extinction of PMS stars is also significantly reduced in the NIR. For these reasons, RV studies on low-mass PMS stars can be delivered with an enhanced precision and a higher signal-to-noise ratio (S/N) in the NIR. Observations in the NIR also favor the detection of substellar companions to T Tauri stars (TTS). TTS

* Based on observations collected with the CRIRES spectrograph at the VLT/UT1 8.2-m Antu Telescope (ESO runs ID 385.C-0706(A) and 093.C-0400(A)) at the Paranal Observatory, Chile.
are young solar analogs (∼1−10 × 10^6 yr) that have spectral energy
distribution (SED) emission that peaks at 1−2 µm. Classical
TTSs (CTTSs) are a subclass that further display observational
evidence of the presence of an accreting circumstellar disk (e.g.,
Bouvier et al. 2007). It is in the rich circumstellar environment of
CTTSs that protoplanets are thought to coalesce and grow in
size (e.g., Pollack et al. 1996). More recently, this idea has been
explicitly reinforced by the findings of Donati et al. (2016),
Johns-Krull et al. (2016) and Mann et al. (2016), who reported
robust evidence of the existence of Jupiter- and Neptune-sized
objects around young TTS (2 Myr and 5−10 Myr, respectively).

One of the most promising CTTS for protoplanetary searches is
AS 205A (≈V866 Sco). It is a young (≈−0.5 Myr) late-type
dwarf (K5) with mean V = 12.4 mag that belongs to a hierar-
chical triple system. At an angular separation of 1.3′′ (≈180 AU
at 140 pc) from AS 205A lies a very low-mass (K7/M0) spectro-
scopic binary (Ghez et al. 1993; Prato et al. 2003; Eisner et al.
2005). An extensive photometric survey by Artemenko et al.
(2010) revealed two distinct and stable periods (P1 = 6.78 and
P2 = 24.78 days) in the power spectrum of the light vari-
tions of AS 205A. The 24-day photometric period was also con-
firmed by Percy et al. (2010). The value of P1 is typical for a
rotational period of a CTTS and is caused by the presence of
cool surface spots. In this context, the anti-phase variations of
the (U − B) color can be explained as chromospheric emission
related to the cool spots. The phase diagram for P2, on the
other hand, shows modulation in brightness and red colors,
which indicates the presence of a cool source. Since AS 205A is
about 2 mag brighter than AS 205B (Herbig & Bell 1988) in the
V band it was concluded that the observed modulated signal (V =
0.25 mag) belongs to the primary or to its circumstellar environ-
ment. The mass of AS 205A, as derived from its stellar tempera-
ture and bolometric luminosity (Andrews et al. 2009), and using
the recently released pre-evolutionary tracks from Baraffe et al.
(2015), is expected to be close to solar (≈9 M_\odot). According to
Artemenko et al. (2010), the period P2 should correspond to the
Keplerian location of an unknown close companion of AS 205A
which perturbed the accretion disk with density waves. The or-
bit was predicted to have semimajor axis of ≈0.18 AU, which is
close to the inner disk radius R_in = 0.14 AU, measured by
Artemenko et al. (2010) further interpreted the light variations of
P2 as the effect of scattering or extinction in the disturbed disk
near the dust sublimation radius.

In this work we derived precise multi-epoch NIR RVs to in-
vestigate the origin of period P2 and searched for the presence of
a low-mass companion. We report here our results and briefly
discuss the implications of the study.

2. Observational method and data reduction

High-resolution observations of AS 205A were conducted in
the NIR, most specifically in the H-band where CTTS pho-
tospheric information can be accessed. Spectroscopic observa-
tions were carried out in good seeing conditions (∼0.8′′) be-
tween Apr. 22, 2010, and May 1, 2014, using CRIRES, the NIR
high-resolution spectrograph mounted on the UT1 telescope at
Paranal Observatory (ESO). AS 205A was visited eight times
during this period. Spectra were collected using the 4096 × 512
pixel Aladdin III detectors and a 0.2′′ slit which delivered
a R ∼ 100,000 around 1598.0 nm (CRIRES setup 36). This par-
cular setting was chosen because we could benefit from the
CO2 telluric atmospheric lines as simultaneous wavelength cal-
ibrators (Huélamo et al. 2008; Figueira et al. 2010c) to derive
precise RVs. Previous studies have indeed shown that telluric
lines are steady RV zero-point tracers (Figueira et al. 2010b) that
development a long-term stability and, for this reason, can deliver RVs
with a precision down to 5−10 ms^{-1}. Final data were acquired in 2
AB nodding cycles with an average S/N ∼ 20 per pixel and an
expected final precision of around 30 ms^{-1}, sufficient, according
to our simulations, to spot an object of a few to several Jupiter
masses at the estimated photometric period of 24.78 days.

In addition to the AS 205A data, we also collected spec-
tra of telluric standard stars (featureless early-type B stars) ob-
tained with similar airmass and instrumental setup to AS 205A.
All observations were taken back-to-back with a RV standard
HD 192310 (K2V) of similar spectral type to examine the preci-
sion of our RV measurements along the time span of our survey.

Reduction was performed using an optimized IRAF-based
pipeline (see Viana Almeida et al. 2012, for more details).
In summary, all spectra were nonlinearity-corrected, dark-current
subtracted, flat-fielded, sky-subtracted (through subtraction of
opposing nodded spectra) and optimally extracted using the
Horne (1986) algorithm. Owing to the blending of telluric and
stellar lines in the final spectra, we also performed telluric re-
moval by dividing each extracted spectrum by the spectrum of
telluric standards stars.

Wavelength calibration was performed using telluric absorp-
tion lines (see e.g., Figueira et al. 2010c; Bailey et al. 2012).
Laboratory wavelength zero-points of each telluric spectral
line were collected from the HITRAN database (Rothman &
Gordon 2009). The RVs in this study were derived using the
Figueira et al. (2010c) pipeline and its adapted version to young
stars developed by Viana Almeida et al. (2012). Both versions
of the pipeline are based on a two-dimensional (2D) cross-correlation function (CCF) inspired by TODCOR
(Mazeh & Zucker 1992). They were specifically built to derive
the RV of an object relative to the zero-point established by
the telluric lines.

To determine the barycentric RVs we cross-correlated each
noded spectrum against the spectra supplied by the NIR
PHOENIX synthetic database (Husser et al. 2013) and against
the spectra of HD 192310 observed on the same date. Two-
dimensional CCFs were fitted using Gaussian function profiles.
Wavelength solutions, barycentric Julian dates and RVs were
then adjusted to the center of mass of the solar system using

3. Analysis

3.1. Rotation and stellar models

To obtain the best-fitting template for cross-correlation and
determine the projected equatorial velocity (v sin i) of the target
we used the effective temperature/SpT scales of Luhan et al.
(1998) to select a subset of PHOENIX models compatible with
the photospheric properties of AS 205A. From the PHOENIX
database we collected models with effective temperatures (T_eff)
-ranging from 4100 to 4700 K, surface gravities (log g) between
3.5 and 4.0 (typical values found in TTS), and metallicities
([Fe/H]) ranging from −0.5 to 0.5 dex. The abundances of α ele-
ments were considered solar.

We then used the gauss task from the IRAF package to de-
grade the resolution of the synthetic models (R ∼ 500,000)
in order to match that of our observations. Using a stellar rotation
broadening kernel, we applied v sin i, which ranged from 6 to
20 km s^{-1}, to the models creating a wider grid of models. We
finally used a routine to interpolate through the models to find

A&A 600, A84 (2017)
the model that minimized the chi-square ($\chi^2$) statistics and best adjusted the spectrum of AS 205A. Figure 1 shows one of the best-fit models. The final stellar parameters of our best model were $T_{\text{eff}} = 4300$ K, $\log g = 3.5$ cm s$^{-2}$, $[\text{Fe/H}] = 0.0$ dex, and $v \sin i = 11$ km s$^{-1}$.

Keeping these parameters in mind, if we assume a TTS radius of 3.7 $R_\odot$ (as provided in Andrews et al. 2010) and a system inclination of $\sim 23.6^\circ$ (given by Artemenko et al. 2012) we calculate a rotational period of $P \sim 6.8$ days, which is in close agreement with previous results for $P_1$ from Artemenko et al. (2012). Curiously, the $v \sin i$ found by iteratively fitting the models is also close to the estimates used in Artemenko’s publication. It can be seen that the rotational period is clearly not of the order of the period $P_2$ of 24.78 days encountered in the studies of Artemenko et al. (2010) and Percy et al. (2010). The apparent disparity between the two periods may seem to reinforce the idea that $P_2$ is of companion origin and not rotationally driven, but a possible relation between $P_1$ and $4 \times P_2$ cannot be completely ruled out and should be investigated further in the future with a larger data set.

### 3.2. Radial velocities

The RV measurements for each date are shown in Table 1 and plotted in Fig. 2. They are the result of the correlation of the spectral information sampled in Detectors 1, 2, and 4 of the selected CRIRES setup (containing $\sim 15$ absorption lines). Final RV uncertainties were calculated dividing the rms of each RV measurement by the square root of the number of independent exposures acquired in each date. The average error bar of the data is $\sim 85$ ms$^{-1}$. The reason for this large value is essentially due to the increased level of blending of stellar and telluric lines in some of the spectra. Telluric removal in these cases is less efficient and is known to decrease the S/N of the final spectra, hence the final precision of the measurements.

As mentioned before, in order to check for possible drifts in the long-term RV measurements obtained using our methodology, we retrieved RVs of a control star (HD 192310) over the time span of the study. In order to keep the same instrumental profile and reproduce the same observation conditions as in our scientific target, spectra of HD 192310 were observed back-to-back with AS 205A. Pepe et al. (2011), using high-resolution spectroscopy, published the Keplerian solutions of two orbiting planets around HD 192310. The dispersion of their RV measurements, however, had a rms of only 2.6 ms$^{-1}$ over a 6.5 yr interval. Our own study detected variations in the HD 192310 RV profile with a standard deviation of $\leq 11$ ms$^{-1}$ over 4 yr of observations. Although it was beyond our detection limit we tried nevertheless to adjust the Keplerian solutions of Pepe et al. (2011) to the variations observed. The lack of consistent fits implied that the dispersion in our RV data was instead associated with the internal uncertainty of our method.

For the sake of clarity, we plot the RV measurements of HD 192310 along with those of AS 205A in Fig. 2. As we can see in this figure, the RV variations of HD 192310 over the entire study are comparatively small, providing solid evidence that observational uncertainties are not at the origin of the RV variations observed in the classical T Tauri stars. The RVs of HD 192310 seem therefore to confirm the stability and precision of the results obtained for AS 205A.

### 4. Discussion

#### 4.1. Preliminary orbital parameters

Using the RVs from Table 1 we found preliminary Keplerian orbital solutions for the suggested companion. For these...
calculations we considered a primary mass as estimated from the recently released pre-evolutionary tracks of Baraffe et al. (2015) which present significant improvements over older tracks commonly employed in previous studies on AS 205A, such as those from Siess et al. (2000). We used the Systemic code to fit a Keplerian solution to the RV measurements. To find the best orbital parameters, first we fixed the Period at 24.78 days and the eccentricity at null value while letting all the other parameters converge.

As soon as we obtained preliminary approximations for the systemic velocity $V_{\text{sys}}$, longitude of periastron $\omega$ and $m_2 \sin i$, we fine-tuned the results by letting all the orbital parameters converge simultaneously. In Fig. 2 we present the best Keplerian curves for photometric period $P_2$ from Artemenko et al. (2010) and the period that best-fitted our RV data. The overall rms and the reduced chi-square ($\chi^2_{\text{red}}$) of the solution using a period of 24.78 days were of 421 ms$^{-1}$ and 66.1, respectively. Conversely, when minimizing the rms of the fit, after some iterations, we obtain a period of 24.84 days with a much lower rms of 73.4 ms$^{-1}$ and a $\chi^2_{\text{red}}$ of 1.07. This $\chi^2_{\text{red}}$ of the $P \sim 24.84$ day solution found for the RV data suggests a good fit to the data. Therefore, it seems that this period better explains the results. In Table 2 we display the orbital elements for the 24.84 day period final fit. The uncertainties depicted are confidence intervals provided by the bootstrap method. We resampled the original data set 100 000 times and fitted a Keplerian solution to each resampled set thereby producing distributions for each orbital parameter. We note that the degrees of freedom of the orbital solution almost equals the number of data points. This implies that we must be cautious when interpreting of the results.

### Table 2. Orbital parameters for the substellar companion.

<table>
<thead>
<tr>
<th>Orbital parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{orb}}$ (days)</td>
<td>24.84 ± 0.03</td>
</tr>
<tr>
<td>$m_1$ ($M_\odot$)</td>
<td>0.9</td>
</tr>
<tr>
<td>$m_2 \sin i$ ($M_{\text{Jup}}$)</td>
<td>19.25 ± 1.96</td>
</tr>
<tr>
<td>$K$ (km s$^{-1}$)</td>
<td>1.529 ± 0.16</td>
</tr>
<tr>
<td>$e$</td>
<td>0.34 ± 0.06</td>
</tr>
<tr>
<td>$\omega$ (deg)</td>
<td>94.14 ± 7.67</td>
</tr>
<tr>
<td>Semi-major axis (AU)</td>
<td>0.162 ± 0.04</td>
</tr>
<tr>
<td>$V_{\text{sys}}$</td>
<td>−10.25 ± 0.07</td>
</tr>
</tbody>
</table>

| $\chi^2_{\text{red}}$ | 1.07 |
| $\text{O-C}$ (ms$^{-1}$) | 73.4 |

Future studies should consider further testing of the effects of stellar activity and, more specifically, of rotational harmonics in the RV measurements. Harmonics are expected to affect RVs when rotational modulation of light by stellar spots occurs (see, e.g., Boisse et al. 2011). We made a preliminary test of the presence of such rotational harmonics in our data (using the rotational period calculated in Sect. 3.1.) by fitting sinusoidal functions to the residuals of the Keplerian fits shown in Fig. 2. We were unable, however, to find any coherent signs of the first three rotational harmonics ($P_{\text{rot}}/2$, $P_{\text{rot}}/3$, $P_{\text{rot}}/4$) which could be imprinted in the RV jittering amplitudes. This result and the goodness of the fit of the adjusted Keplerian solution using $P = 24.84$ days increases our confidence that the results presented do not depend on stellar spot modulation. But to further explore these effects we need a better sampling of the RV curve with a higher number of data points. This kind of study would certainly improve the orbital characterization of the reported substellar companion.

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4.3. New perspective on the AS 205A system

Following the results presented here and the results from Artemenko et al. (2010), we suggest the existence of a low-mass companion to AS 205A. We propose that observational evidence of this low-mass companion in previous campaigns could have been hindered by the prolific IR emission observed in AS 205A.

Assuming that the orbit of the planet is aligned with the stellar rotation and that the inclination of the system is between $25^\circ$ (Andrews et al. 2010; Artemenko et al. 2012; Pontoppidan et al. 2011) and $15^\circ$, as the study of Salyk et al. (2014) suggests, then the absolute mass range of the proposed substellar companion would be between $45.6$ and $74.3$ M$_{\text{Jup}}$. This mass range suggests an upper and lower limit in $T_{\text{eff}}$ of around $2200$ K and $1500$ K (see, e.g., Kirkpatrick 2005; Rice et al. 2010), respectively. In this temperature range the object would fall into the temperature-mass domain of ultracool dwarfs or very late-type M stars. Since the peak emission of such objects is located in the NIR range, close to $1.0\mu$m (Cushing et al. 2006; Sarro et al. 2013), its SED could thus be masked by the strong circumstellar IR emission of AS 205A (see, e.g., Andrews et al. 2010). Ideally, new dedicated spectroscopic observations, both high-resolution and high S/N, should be prepared in the near future with the aim of identifying notable spectral features of brown dwarfs or very late-type M stars that could be imprinted in the AS 205A spectrum. Given the very distinct nature of late-type M stars and brown dwarfs (see, e.g., McLean et al. 2007; Rice et al. 2010), this strategy could lead to a successful identification of the spectral type and mass regime of the substellar companion.

Recent sensitive high-resolution mm observations of AS 205A with the ALMA facility (Salyk et al. 2014) revealed an intriguing extended asymmetric profile of the $^{12}\text{CO}$ (2–1) emission. Despite their best efforts, the authors could not explain this emission merely on the basis of a Keplerian gas-disks models and/ or stellar wind parametrization. Indeed, when compared with typical outflows produced in protostars (e.g., Jørgensen et al. 2007), the $^{12}\text{CO}$ emission of AS 205A presents quite distinct and unique characteristics (see, e.g., Salyk et al. 2014). While some of the emission can be associated with tidal stripping from the close binary AS 205B at just $1.3''$, it is unlikely that this phenomenon alone could explain the observations. Arguably, the discrepancies observed may suggest the unaccounted presence of an additional companion to AS 205A. This possibility should be explored in the future if follow-up studies confirm the existence of a close substellar object.

5. Conclusion

It is interesting to note the close agreement between the estimated photometric period $P_2$ (~24.78 days) of Artemenko et al. (2010) and the Keplerian period obtained with our NIR spectroscopy ($P \sim 24.84$ days). Period $P_2$, to the best of our knowledge, does not seem to be a rotational modulation produced by spots in the stellar surface. More RV measurements, however, are necessary in order to confirm these results. Even though unaccounted phenomena such as stellar activity and/or accretion (e.g., Bouvier et al. 2007) could have influenced the spectral profile, the high-precision attained in this study (below 70 ms$^{-1}$ in most of the cases) and the lack of correlation of BIS and RVs variations provide strong support for our companion interpretation. The substellar companion hypothesis is, to the best of our knowledge, the most robust explanation for the results obtained.

The confirmation of a substellar companion at the border of the inner gap of the protoplanetary disk at such an early time (~0.5–1 Myr) could provide interesting constraints on brown dwarf and planet formation theories and on the process in which planets migrate within the circumstellar disk. The AS 205A system remains an important target for exploring these phenomena in the near future.

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