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Properties of the young gas giant planet β Pictoris b

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Abstract

Young systems such as β Pictoris are of great importance as they trace the formation and early evolution of planetary systems. They are also the only targets around which planets can be imaged today. We detected with NaCo a giant planet around β Pictoris, roughly along the dust disk position angle (PA), with a semi-major axis (sma) between 8 and 14 AU. Its observed L' luminosity indicated a 1700 K, 7-11 M_{Jup} mass planet according to "hot-start" models. We obtained the first images of the planet in the J (1.265 μm), H (1.66 μm), and M' (4.78 μm) bands between 2011 and 2012. We used these data to estimate build its 1-5 μm spectral energy distribution (SED) for the companion, and to consolidate previous semi-major axis (8-10 AU) and excentricity (e $\leq$ 0.15) estimates. We compared the SED to 7 atmospheric models to derive T_{eff} = 1700 ± 100 K and log g = 4.0 ± 0.5. We used the temperature and the luminosity of β Pictoris b to derive new mass estimate for the companion. We compared these estimate to independant mass measurments set by the orbital parameters and the radial velocities and use them to derive informations on the formation history of the object.

1. Introduction

High-contrast imaging is just starting to enearth the population of gaz giants planets on wide orbits (8 to several 100 AU) around young stars. These systems challenge the classical core-accretion paradigm proposed for the giant planets of our solar system. The analysis of the flux emited by the planet in the near-infrared (1-5 μm), which can in turn give access to the physical (mass, T_{eff}, log g) and chemical (composition, chemistry) properties of the object.

β Pictoris has become one of the best and most emblematic target for the study of early phasis of planetary systems formation and evolution since the discovery of a extended disk surrounding the star in the 80s, more than a decade before the discovery of the first exoplanet. In 2010, we announced the direct detection at L' band (3.8 μm) of a 7-11 M_{Jup} planet orbiting the star, roughly along the dust disk position angle (PA), with a semi-major axis a between 8 and 14 AU (1). β Pictoris b is so far the closest planet ever imaged around a star. It is one of the rare directly imaged planet that could have formed by core-accretion.

2. Follow-up of β Pictoris b

Since 2011, we performed follow-up observations of the system with the NaCo adapative optics-fed imager at VLT/UT4. We used new observations at 2.18 μm (K_s band), 4.05 μm (2; 3), and L' band to confirm that the companion is in the planetary mass range and is placed on an inclined orbit with respect to the disk midplane (4) characterized by a semi-major axis of 8-10 AU and a low excentricity (5).

We obtained, more recently, new angular differential imaging (6) observations of the star in the J (1.265 μm), H (1.66 μm), and M' (4.78 μm) bands. These new data enable to detect for the first time the planet at these wavelengths (Figure 2). We combined our new astrometric data point to those reported in (5) and fit orbits using Levenberg- Marquardt algorithm (LSLM) and Markov-Chain Monte-Carlo (MCMC) simulations. We confirm that the semi-major axis falls in the 8-10 AU range with a probability higher than 80%. Subsequently the orbital period ranges between 17 and 25 years and the planet eccentricity is confined to ≤0.15 with similar probability. These up-to-date constraints combined to present constraints coming from radial velocity measurments (7) are used to set upper limits of 12 and 15.5 M_{Jup} on the planet mass for semi-major axis of 9 and 10 AU respectively.

We derive contrasts of $\Delta J = 10.5 \pm 0.3$, $\Delta H = 10.0 \pm 0.2$ mag and $\Delta M' = 7.5 \pm 0.2$ mag. The photometry and colors are similar to those of other young early-L dwarfs and planetary mass companions. We used them to derive the bollometric luminosity of the planet $\mathrm{Log}_{10}(L/L_{\odot}) = 3.87 \pm 0.08$. The new measurment complete the 1-5 μm SED of the planet (Figure 2). We compared the SED to synthetic fluxes predicted by seven grids of atmospheric models (AMES-DUSTY, AMES-COND, BT-COND, BT-DUSTY, BT-Settl2010 and 2012, DRIFT-PHOENIX). These models account for the limiting and intermediate cases for the formation of dust clouds in the atmospheres of brown-dwarfs and exoplanets. They compute the emerging flux at top of the photospheric layers at given wavelengths for a grid of effective temperatures (T_{eff}), surface-gravities (log g) and metallicities ([M/H]). The models confirm that the planet has a dusty atmosphere with $T_{\rm eff}$ = 1700 ± 100 K. They suggest in addition that the planet has a surface gravity typical of young objects (log g=4.0 ± 0.5). The results are not influenced by the undetermination of the metallicity.

We use the temperature and luminosity to derive a mass of $10^{+3}_{-2}\mathrm{M_{Jup}}$ and $9^{+3}_{-2}\mathrm{M_{Jup}}$, respectively, for β Pictoris b using evolutionary models of (8) and (9). These models consider the object

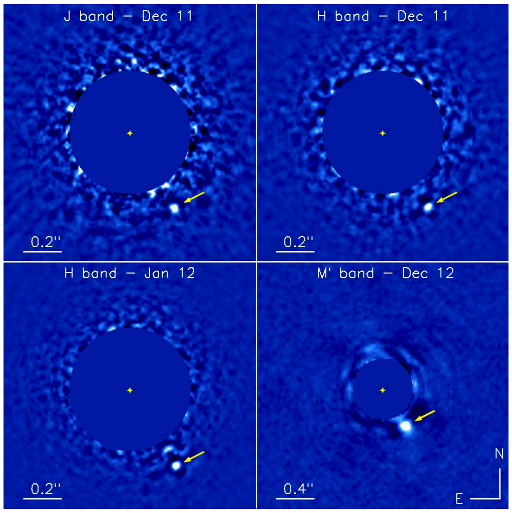

Figure 1: β Pictoris b (arrows) re-detected in the J (upper-left panel) band, in the first (upper-right panel) and second epochs (lower-left panel) H band observations, and in the M' band (lower-right panel).

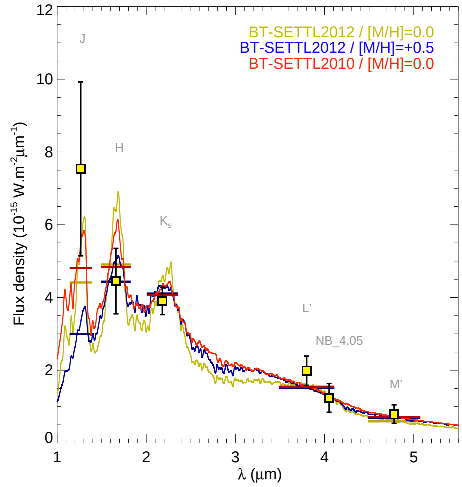

Figure 2: Comparison of the apparent fluxes of β Pictoris b (yellow squares) to best fitted fluxes (horizontal barres) generated from synthetic spectra.

starts its evolution from arbitrary initial conditions, not including any accretion processes (“hot-starts"). We then also considered the alternative and evolutionary models that consider that a fraction (“warm-start") or all (“cold-start") the gravitational energy of the accreted material is radiated away at an accretion shock before beeing incorportated to the planet (11; 10). Only the “hot-start" models and “warm-start" models with intermediate to high initial entropies can predict masses in agreement with the upper limit set by radial velocities.

3. Conclusions

This study constitutes the most complete characterization of the system to date. The high initial entropy, or equivalently the failure of evolutionary models with “cold-start" conditions, could mean that β Pictoris b formed via the disk instability mechanism. Nevertheless, disk-instability models can not easily explain an in-situ formation of the planet, and a formation at larger separation combined to inward migration mechanisms must be invoked. Conversely, we use the planet population synthesis code of C. Mordasini (Mordasini 2009, 2012) to demonstrate that the planet could still originate from core-accretion, althought it would remain at the edge of the capabilities of this mechanism. We also argue that the initial conditions can not be as easily related to the formation process as thougth.

β Pictoris b will likely be used as a reference target for the science verification of the planet imagers SPHERE and GPI next year. These two facilities should pursue the monitoring of the planet orbital motion, at a time when it should be close to periastron. The intruments should also easily provide the first low- resolution (R~400) near-infrared (1-2.5 μm) spectrum of the planet. Spectral features, such as the pseudo-continuum shape from 1.5 to 1.8 μm, will enable to firmly confirm the intermediate surface gravity of the companion. We could also expect to estimate the metallicity (possibly from the shape of the K-band pseudo-continuum) of the planet.

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