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# EXOCOMETS IN THE DISK OF TWO YOUNG A-TYPE STARS

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**Abstract.** Optical spectra of the 20 Myrs old A-type stars $\beta$ Pictoris and HD172555 have been collected between 2003 and 2011 with the HARPS instrument installed at the La Silla 3.6m telescope. In the two stellar absorption lines composing the Ca II doublet at 3950Å, we observed for these two targets narrow and doppler-shifted variable absorption features, which in the case of $\beta$ Pictoris were known to occur since 1987. These transient signals are interpreted by the passage of orbiting evaporating bodies in front of the stellar disk, or transits of exocomets. We collected 493 individual detections of independent exocomets around $\beta$ Pictoris allowing us to perform an unprecedented statistical studies of their physical properties (Kiefer et al. 2014a). Moreover, we report the detection of 4 transits of exocomets in front of the young A-type star HD172555; thus promoting this system as the second with simultaneous detection of exocomet transits in both lines of the Ca II doublet (Kiefer et al. 2014b).

Keywords: Exocomets, Beta Pictoris, HD172555

## 1 Introduction

The studies of young planetary systems, still forming or having yet formed planets, may unshade mysteries on the nature of our own Solar System as it was, 4.5 billion years ago. The system of the 20 Myrs old $\beta$ Pictoris appears as a prototype for the young Solar System, and as such attracts a lot of attention since 30 years (Vidal-Madjar et al. 1998). This A5V star located at 19pc from Earth harbours plenty of features: a wide, warped and asymmetrical debris disk extending in both directions to more than 1000 AU from the star, an $8\,M_J$ planet $\beta$ Pic b, and minor bodies such as comets, occasionnally grazing onto the star and producing the absorption signatures we are here reporting.

Several intriguing features of the $\beta$ Pic disk find now explanations; among them, the asymmetry, possibly due to a clump produced by a collision between planetesimals at tenth of AU from the star (Dent et al. 2014, Telesco et al. 2005); the warp, compatible with the action of $\beta$ Pic b on the disk (Mouillet et al. 1997); a stable gas disk at a couple of AU from the star standing still thanks to a braking effect due to a massive amount of carbon elements (Roberge et al. 2006); and the transient absorption in the stellar lines, identified as being due to exocomets (Ferlet et al. 1987, Beust et al. 1990, Vidal-Madjar et al. 1994). These all participate to build a comprehensive picture of this system, where planet formation happened in the same time as destructive collisions between planetesimals, where the dominating gravitationnal action of possibly the only massive planet present in that system, $\beta$ Pic b, warps the disk from which it is born, and where icy bodies evaporate and replenish the disk in heavy elements such as carbon and oxygen (Lecavelier des Etangs et al. 1996).

Keeping in mind this picture of the system, the observation of exocomets orbiting close to $\beta$ Pictoris does not look strange at all. In a system where planet formation comes with planetesimal destruction, some minor icy bodies of around 10 km size should form and undergo the influence of $\beta$ Pic b to finally end up falling toward the star while evaporating plenty of gas and dust.

Until now, $\beta$ Pictoris is the only known system with such a rich surroundings: planet, debris disk with various features and comets. However, we know that systems with debris disk are common (Booth et al. 2013, Morales et al. 2009, Plavchan et al. 2009, Roberge & Weinberger 2008), but we still lack detections of planets and comets in them. Planets are a challenge to find with the usual radial velocity and transit methods in young systems, mostly because the central star rotates fast and is often very active. However the recent development

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of direct imaging and interferometry already led to the evidence of the presence of planets aroung young stars (eg. Fomalhaut and Vega). But exocomets are even harder to observe. They are impossible to detect with direct imaging, since too faint. The only known method consists to observe narrow variable absorptions in the stellar spectrum. This requires the system to be seen edge-on, making it difficult to gather a large sample of exocomet-hosting young stars. Nevertheless, with luck and because the sample of stars with debris disk becomes larger and larger each year, several systems are seen edge-on and in some of them possible signatures of exocomets have been observed these last few years – such as HR10 (Lagrange-Henri et al. 1990), 49 Ceti (Welsh et al. 2013) and HD172555 (Kiefer et al. 2014b).

Among them, HD172555 is a very interesting system, and in some way resemble $\beta$ Pictoris. It is roughly the same type (A7V) and the same age (12Myr); it harbours a dusty debris disk, although smaller; there is an intriguing excess of gas in the disk (Riviere-Marichalar et al. 2012); and a super-collision between planetesimals possibly occurred at 5 AU from the central star (Lisse et al. 2009). However, any planet has ever been discovered around it, in possible relation to the smallness of the disk, the super-collision, and the presence of a companion at 1000 AU.

In the first section, we report the detection of 493 exocomets passing in front of $\beta$ Pictoris between 2003 and 2011 using archival data from the HARPS spectrograph (Kiefer et al. 2014a). The large size of this sample allowed us to conduct a statistical analysis of these objects. We discovered two families of exocomets orbiting $\beta$ Pictoris. We show that they are physically distinct and thus differentiate by their origin. A first family, composed of aged comets depleted in volatile, is observed in an orbital evolution compatible with a mean-motion resonance mechanism induced by $\beta$ Pic b. A second family, composed of fresher objects emitting volatiles 10 times more efficiently, roughly share a common orbit, compatible with the fragmentation of a bigger body, such as Shoemaker-Levy 9 or the Kreutz family in the Solar System.

In the second section, we report the detection of 4 exocomets passing in front of HD172555 using archival data collected with the HARPS spectrograph from 2004 to 2011 (Kiefer et al. 2014b). This is the second star after $\beta$ Pictoris, around which we detect exocomets in both lines of the Ca II doublet. This allowed us to deduce the size of their cometary cloud and an estimation of their opacity.

## 2 The two families of exocomets in the disk of $\beta$ Pictoris

Between 2003 and 2011, a total of 1106 optical spectra of $\beta$ Pictoris have been collected with HARPS. As can be seen on Fig. 1, the Ca II doublet of $\beta$ Pictoris presents at any time two main kind of features: a stable line centred at the star's radial velocity 21 km s$^{-1}$; and several narrow day-variable lines centred on radial velocities ranging from -150 to 200 km s$^{-1}$. The first kind of feature is the absorption line signature of a circumstellar gas disk seen edge-on, while the second kind of features is firmly identified to evaporating bodies, or exocomets, crossing the line of sight at different distances to the star (Beust et al. 1990, Ferlet et al. 1987).

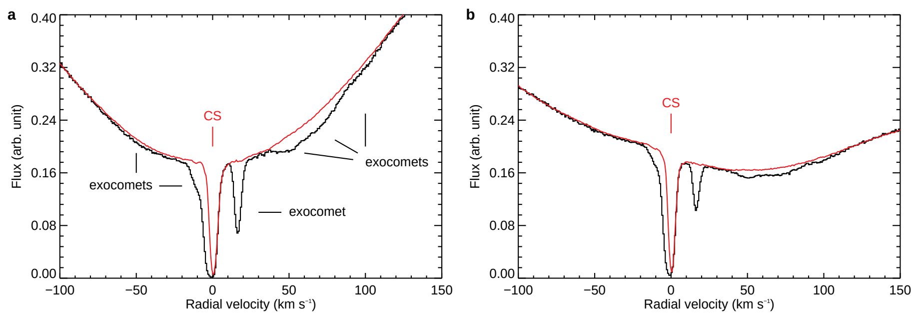


**Fig. 1.** This figure shows a typical spectrum of the Ca II doublet of $\beta$ Pictoris obtained on 27 October 2009. **Left:** the Ca II-K line at 3934.66Å, with exocomets' transit signature identified; **right**: the simultaneously observed Ca II-H line at 3968.47Åwith the same signatures at the same velocities. The red line denote the reference spectrum derived from the data and CS indicates the stable circumstellar line. Radial velocities are given in the $\beta$ Pic's rest frame. From Kiefer et al. 2014a.

The $\beta$ Pic Ca II spectrum is observed to be stable on 30 min timescales. In order to limit any spurious spectral variability, while keeping track on variable comet's signatures, we resampled the 1106 HARPS spectra into 357 spectra separated by at least 10 min, averaging together all spectra collected in the same 10 min time interval. We then normalized each spectrum by the quiet reference spectrum, that we derived thanks to the large set of flux data points and depicted in red in Fig. 1. This led to normalized spectra showing exclusively features due to exocomets' transit. We fitted simultaneously each feature in the K and the H lines by a Gaussian depending on $p_{K,H}$ the K and H line depths, $v_0$ the central radial velocity, and $\Delta v$ the linewidth FWHM,

$$p_{K,H}\, e^{4\ln 2\frac{(v-v_0)^2}{\Delta v^2}} \qquad \text{with} \quad p_K = \alpha e^{-A} \quad \text{and} \quad p_H = \alpha e^{-A/2}. \tag{2.1}$$

Because the depths of both Ca II K and H lines depend on the size ($\alpha$) and the opacity ($A$) of the occulting cloud, and because we were able to probe both K and H lines in the same time, we could derive the size and the opacity of each detected cometary cloud. The size $\alpha$ measures the portion of the stellar disk occulted by the cometary cloud; it ranges between 0 and 1. In addition, we selected among all the detections a sample of 493 individual detections of independent exocomets. This allowed us to observe the presence of two clusters of detections: deep lines on one side ($p_K$>0.4) and shallow lines on the other side ($p_K$<0.4), as seen in Fig. 2 (left). The radial velocity and FWHM distributions of these two populations were clearly distinct. We could relate these observable quantities to physical quantities characterizing how the nuclei of the comets evaporate and which orbit they follow.

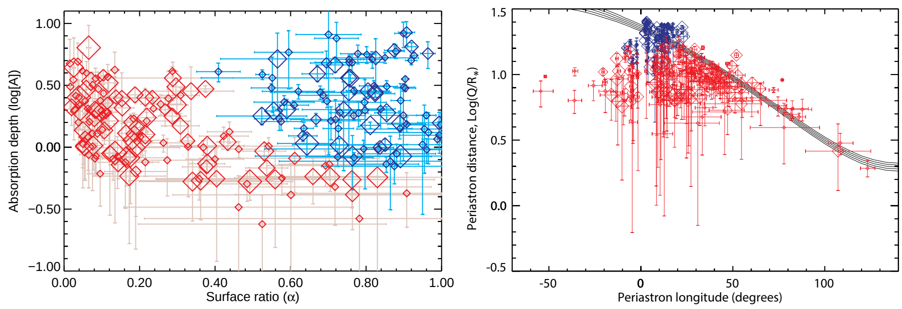


**Fig. 2. Left:** Diagram showing $\alpha$, the portion of the star occulted by the cometary cloud, against $\log A$, a measure of the cloud's opacity for the 252 exocomets detected with $\alpha$<1. Two clusters of data points are visible in this figure. They correspond, in blue, to the deep line population ($p_H$<0.4), and in red, to the shallow line population ($p_K$<0.4). The smallest data points correspond to data taken in 2003 and the largest data points to data taken in 2011. **Right:** This diagram shows the difference of distribution of exocomets' periastron distance with respect to periastron longitude between the two families. The black solid lines depict the expected evolution of orbits of small bodies in 4:1 mean-motion resonance with a jovian-mass planet at 5 AU from the central star. From Kiefer et al. 2014a.

Focusing on the exocomets occulting a portion of the star smaller than the stellar disk ($\alpha$<1), we determined that the comets of the deep lines population, or population D, are ten times more efficient to reprocess incident stellar radiation into gas and dust evaporation than the comets of the shallow lines population, or population S. We also determined that the orbits of the population S exocomets follow a pattern compatible with a 4:1 mean-motion resonance mechanism with $\beta$ Pic b (Beust & Morbidelli 1996, Thébault & Beust 2001); while the orbits of the population D exocomets scatter around a common orientation and periastron distance ($Q_D \simeq 18\pm4 R_\star$; $\varpi_D \simeq 7\pm8°$) as would happen in the case of the break-up of at least one bigger body (Fig. 2, right), much like the Kreuz Family in the Solar System. This is to be compared to the scattering of the orbits of population S with $Q_S \simeq 9\pm3 R_\star$ and $\varpi_S \simeq 22\pm25°$.

These results suggest that the two populations have distinct origin and therefore compose two distinct families of exocomets; one being a family of exhausted icy bodies that underwent a series of passage at close distance to the star, and the second being a family of fresher icy bodies possibly remnants of the fragmentation of one or a few bigger bodies.

## 3 Exocomets in the disk of HD172555

Between 2004 and 2011 a total of 129 spectra of HD172555 have been collected with HARPS, distributed on 22 nights of observations. The quiet Ca II spectrum of HD172555 is composed of two main features, an interstellar medium shallow absorption line at -19 km s$^{-1}$, and a central stable absorption line in both Ca II-K and Ca II-H lines. The first is identified to the G cloud of the local interstellar medium (ISM); while the second is identified to a circumstellar gas component, as for $\beta$ Pic, yet shallower (Kiefer et al. 2014b). This is deduced from *i)* the lack of such absorption line in the Na I doublet at 5890Å, *ii)* the correspondance of the central radial velocity of this component to the redshift velocity of the star ($2\,\mathrm{km\,s^{-1}}$), and *iii)* any ISM component is expected at that redshift. The non-detection in Na I yields a 5-$\sigma$ upper limit for the equivalent widths ratio of $EqW(\mathrm{Na\,I}\,D_2)/EqW(\mathrm{Ca\,II}\,K)$<0.04. This upper limit is much lower than typical values seen in the local interstellar medium where it is usually greater than 0.1 (see, e.g., Welsh et al. 2010). We thus concluded on the circumstellar nature of this feature.

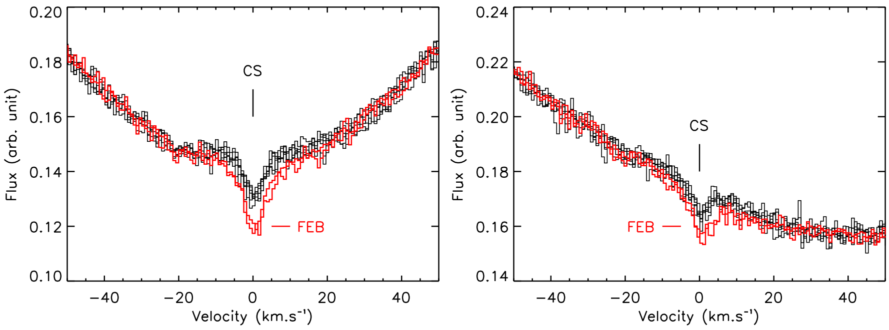


**Fig. 3.** Plot of HD172555 spectra of 2004. **Left:** the Ca II-K line; and **right:** the Ca II-H line. Two typical spectra on 22 September 2004 separated by a 6 minute-time interval (red lines) clearly show the presence of an additional absorption at the star's radial velocity in comparison to spectra obtained 100 days earlier (black lines). Velocities are given in the star's rest frame. From Kiefer et al. 2014b

But, transient events very similar to the variable absorption features of $\beta$ Pic could also be observed on these spectra. As can be seen on Fig. 3, a significant narrow variable absorption is clearly detected in both Ca II-K and Ca II-H lines on the 22 September 2004 at the star's radial velocity. Three similar events were observed on 21 August 2005, 8 July 2010 and 11 July 2011. These are obviously due to the passage of occulting $Ca^+$ clouds in front of HD172555. Table 1 summarizes the properties of these occulting clouds that we derived by fitting the absorption lines, as for $\beta$ Pic above.

| Date | | K line Depth | Velocity | FWHM | Surface Ratio | Optical depth |
|---|---|---|---|---|---|---|
| (MJD) | (D/M/Y) | | (km/s) | (km/s) | $\alpha$ | |
| 53269.996 | 22/09/04 | $0.059 \pm 0.003$ | $0.35 \pm 0.37$ | $13.9 \pm 0.9$ | $\geq 0.9$ | $0.061 \pm 0.003$ |
| 53270.134 | 22/09/04 | $0.072 \pm 0.006$ | $2.3 \pm 0.5$ | $19.5 \pm 1.2$ | $\geq 0.84$ | $0.075 \pm 0.006$ |
| 53603.145 | 21/08/05 | $0.034 \pm 0.004$ | $13.5 \pm 1.5$ | $38.4 \pm 9.7$ | $0.04^{+0.04}_{-0.01}$ | $1.69 \pm 1.05$ |
| 55385.285 | 08/07/10 | $0.029 \pm 0.006$ | $1.26 \pm 1.07$ | $18.4^{+7.9}_{-10.1}$ | $\geq 0.024$ | $\leq 10.3$ |
| 55723.248 | 11/06/11 | $0.037 \pm 0.002$ | $-1.6 \pm 0.5$ | $22.5 \pm 3.2$ | $0.04 \pm 0.01$ | $1.90 \pm 0.63$ |
| 55723.280 | 11/06/11 | $0.032 \pm 0.002$ | $-2.44 \pm 0.51$ | $24.9 \pm 3.3$ | $0.04 \pm 0.01$ | $1.48 \pm 0.51$ |
| 55723.309 | 11/06/11 | $0.030 \pm 0.003$ | $-3.24 \pm 0.73$ | $24.2 \pm 4.7$ | $0.04^{+0.02}_{-0.01}$ | $1.59 \pm 0.78$ |

**Table 1.** Table of the fit parameters with 1-sigma error bars. The upper and lower limits are given at the 1-sigma level. From Kiefer et al. 2014b.

Two types of clouds seem to be detected, if we compare the two most significant events (22/09/04 and 11/06/11): large and optically thin on one side, compared to small and opaque on the other side. There is no significant difference in the radial velocities, but the linewidth differ.

The fact that the measured surface ratio is well less than 1 for at least one of the most significant component, strongly suggests that we are witnessing the transit of cometary clouds in front of HD172555. The differences of the measured properties of these clouds can be explained as for $\beta$ Pic's comet if the comets are detected at different distance to the star at the transit time. In this context, the similarity in radial velocities would be explained by different orientation of the respective orbits. This is usual observations on exocomets of $\beta$ Pictoris.

## 4 Conclusions

The discovery of two families of exocomets orbiting $\beta$ Pictoris leads to two main conclusions. First, the expected 4:1 mean-motion resonance mechanism induced by $\beta$ Pic b dragging icy bodies towards the star is compatible with our observations. This indicates that if the planet is located at around 10 AU from the star, a reservoir of icy bodies exists at around 4 AU. This of course questions the origin of this 'belt' of icy planetesimals. The most straightforward answer would be that these bodies are the remnant of planet formation in the disk of $\beta$ Pictoris. More investigations should be conducted on this question. Second, the observation of comets possibly originating from the break-up of a bigger bodies (like the Kreuz family in the solar system) and the emphasis of mean-motion resonance mechanism in the $\beta$ Pic system, make this system even more similar to ours, and strengthen the identification of $\beta$ Pic to a young solar system.

We also reported the discovery of exocomets orbiting the system of the young star HD172555, and the identification of a circumstellar gas disk feature. One of the main conclusions from these discovery is that the system should be seen almost edge-on. Morever, the system HD172555 appears then more and more similar to $\beta$ Pictoris, in which the presence of a stable circumstellar gas disk can be explained by the evaporation of minor bodies, or comets. Since both features are detected around HD172555 it is tempting to invoke this relation to connect the presence of a circumstellar gas disk to the detection of exocomets. Future investigations will determine if this relation is real or not. Finally, the firm observation of exocomets in an other system brings hope to possibly observe exocomets in other young systems. Future observations of 30 young A-B type stars with HARPS are planned and will be dedicated to the search of exocomets.

## References


Beust, H., Vidal-Madjar, A., Ferlet, R., & Lagrange-Henri, A. M. 1990, A&A, 236, 202

Beust, H., & Morbidelli, A. 1996, Icarus, 120, 358

Booth, M., Kennedy, G., Sibthorpe, B., et al. 2013, MNRAS, 428, 1263

Dent, W. R. F., Wyatt, M. C., Roberge, A., et al. 2014, Science, 343, 1490

Ferlet, R., Vidal-Madjar, A., & Hobbs, L. M. 1987, A&A, 185, 267

Kiefer, F., Lecavelier des Etangs, A., Augereau, J.-C., et al. 2014, A&A, 561, LL10

Kiefer, F., Lecavelier des Etangs, A., Boissier J., et al. 2014, Nature, 514, 462

Lagrange-Henri, A. M., Beust, H., Ferlet, R., Vidal-Madjar, A., & Hobbs, L. M. 1990, A&A, 227, L13

Lecavelier des Etangs, A., Vidal-Madjar, A., & Ferlet, R. 1996, A&A, 307, 542

Lisse, C. M., Chen, C. H., Wyatt, M. C., et al. 2009, ApJ, 701, 2019

Morales, F. Y., Werner, M. W., Bryden, G., et al. 2009, ApJ, 699, 1067

Mouillet, D., Larwood, J. D., Papaloizou, J. C. B., & Lagrange, A. M. 1997, MNRAS, 292, 896

Plavchan, P., Werner, M. W., Chen, C. H., et al. 2009, ApJ, 698, 1068

Riviere-Marichalar, P., Barrado, D., Augereau, J.-C., et al. 2012, A&A, 546, L8

Roberge, A., Feldman, P. D., Weinberger, A. J., Deleuil, M., & Bouret, J.-C. 2006, Nature, 441, 724

Roberge, A., & Weinberger, A. J. 2008, ApJ, 676, 509

Telesco, C. M., Fisher, R. S., Wyatt, M. C., et al. 2005, Nature, 433, 133

Thébault, P., & Beust, H. 2001, A&A, 376, 621

Vidal-Madjar, A., Lagrange-Henri, A.-M., Feldman, P. D., et al. 1994, A&A, 290, 245

Vidal-Madjar, A., Lecavelier des Etangs, A., & Ferlet, R. 1998, Planet. Space Sci., 46, 629

Welsh, B. Y., Lallement, R., Vergely, J.-L., & Raimond, S. 2010, A&A, 510, A54

Welsh, B. Y., & Montgomery, S. 2013, PASP, 125, 759