β Pictoris, a Laboratory for Planetary Formation Studies

Anne-Marie Lagrange[1]
Gaël Chauvin[1]

[1] Institut de Planétologie et d'astrophysique de Grenoble, France

Shortly after its discovery in 1984, the Beta Pictoris disc was recognised as a possible site of past, ongoing or future planet formation. It has since been observed extensively, from the X-ray domain to centimetre wavelengths by many ground- and space-based telescopes. The disc has become a remote laboratory to study the physical and chemical characteristics of debris discs. Recently, we were able to detect a companion orbiting the star at a distance comparable to that of Saturn in our Solar System. The β Pic system thus offers a unique opportunity to study giant planet properties and planet/disc interactions. We present a short — and necessarily incomplete — review of the main discoveries made in this fascinating system over three decades of observations, a number of which were achieved with ESO telescopes.

The debris disc, its gas and kilometre-sized bodies

One of the most challenging topics in astronomy today is certainly to understand how planetary systems, with all their complexity (planets, comets, dust and gas) form and evolve. Even though sketches of the formation of the Solar System have been developed and simulated since the late 1960s, additional examples of planetary systems were lacking to explore their possible variety. The discovery of infrared (IR) excesses associated with T Tauri stars and then with main sequence stars were the first steps in the study of star and planet formation. In 1984, IRAS measured IR excesses associated with a few main sequence stars that were attributed to cold dust, perhaps related to planet formation (Aumann, 1984). Shortly after, Smith & Terrile (1984) imaged the dust around one such star, a young (12$^{+8}_{-4}$ Myr) and close (19.3 ± 0.2 pc) A5V star β Pic (note that at that time, its age was rather estimated to be 200 Myr, and its distance 16 pc). The dust distribution revealed a flat, edge-on disc, detected between 100 and 400 astronomical units (au) from the star. The β Pic disc became a prototype of the debris discs that contain substantial amounts of grains, short-lived against destructive (collisions) or removal (radiation pressure, Poynting–Robertson drag) processes and therefore needing replenishment through collisional cascade or evaporation from large, kilometre-sized bodies down to micrometre-sized grains.

Debris discs trace the stages of planetary system evolution where solid bodies significantly larger than primordial dust are present (see Lagrange et al. [2000] for an early review). Since 1984, the β Pic disc has been extensively observed from optical to millimetre wavelengths (see Figure 1). Briefly, optical and near-IR observations have provided high spatial resolution, scattered light images tracing small grains; thermal data provided by medium resolution images have demonstrated the presence of hotter dust, while (sub-)millimetre images have traced larger grains, and consequently, the parent bodies as well. Thanks to all these observations, we now have a schematic view of the disc (Augereau et al., 2001; Wilner et al., 2012), in which the parent kilometre-sized bodies are mainly located in a narrow (10–20 au) wide ring at about 90–100 au (planetesimal disc). Collisional cascades produce small grains detected out to several hundreds of au because of the radiation pressure of the star, while an additional component of hotter dust is also needed to account for the IR data.

Shortly after the discovery by dust imaging, circumstellar gas was detected in absorption using high spectral resolution optical spectrographs and in the ultraviolet with the International Ultraviolet Explorer (IUE) satellite. The first optical data were obtained in late 1984 with the high resolution Coudé Echelle Spectrograph (CES) at the Coudé Auxiliary Telescope (CAT) on the ESO 3.6-metre telescope at La Silla (Hobbs et al., 1985; Vidal-Madjar et al., 1986, see Figure 2a). Repeated observations with CES and IUE revealed important infalls of high velocity ionised gas (a few tens to a few hundreds of km/s), packed in clumpy structures with sizes smaller than that of the star (e.g., Lagrange et al.,1988), attributed to evaporating comets grazing the star. Intensive monitoring of these gaseous infall events in the late eighties/early nineties as well as detailed modelling

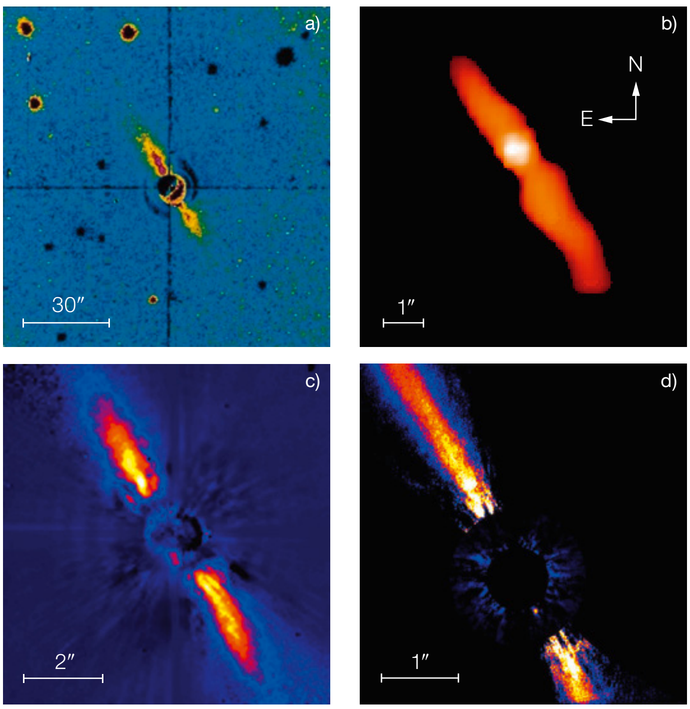


Figure 1. Images of the β Pic disc at various wavelengths: a) optical observations with Las Campanas 2.5-metre at 890 nm obtained in April 1984 (from Smith & Terrile, 1984); b) mid-infrared observations at 12 μm with the ESO 3.6-metre and TIMMI (from Lagage & Pantin, 1994); c) near-infrared coronagraphic imaging in *J*-band with ESO 3.6-metre and the Adonis instrument (from Mouillet et al., 1997); d) near-infrared *Ks*-band images with VLT and NACO (Lagrange et al., 2012a).

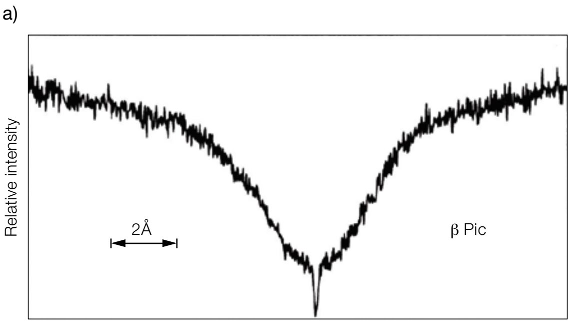
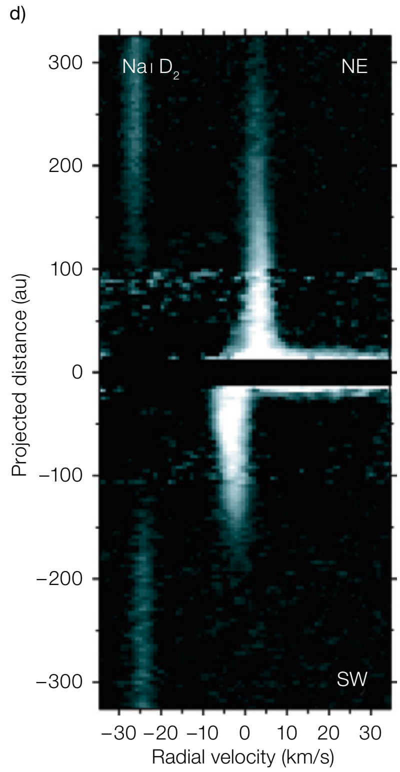
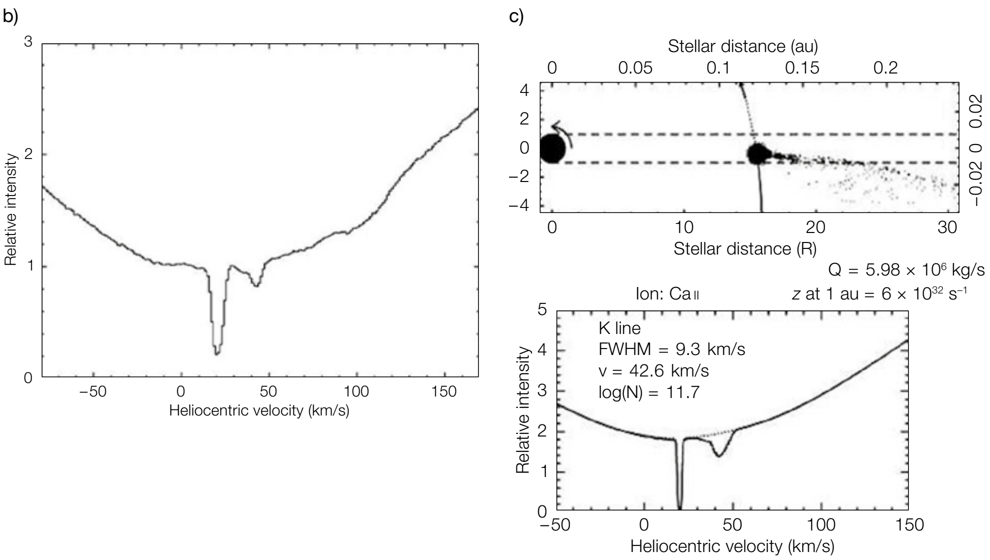


Figure 2. a) Early Ca II spectrum of β Pic (Hobbs et al., 1985): The stable gas produces a deep and narrow component at the bottom of the rotationally broadened stellar line. b) In addition to the centred stable circumstellar line, variable redshifted Ca II is also observed (Vidal-Madjar et al., 1986); from CES data. c) Simulations of the redshifted absorption produced by an evaporating comet grazing the star as illustrated on the small upper panel (from Beust et al., 1990). d) Resolved Na I emission observed in the β Pic disc with VLT UVES; the gas is shown to be on a Keplerian orbit (Brandeker et al., 2004).





(e.g., Beust et al, 1990, see Figure 2c) strengthened the "falling evaporating bodies" (FEB) scenario which still holds after more than 20 years of observations. On the contrary, there is still no consensus concerning the explanation for the stable gas around the star, seen either in absorption or in emission, in particular species that are expected to be very short-lived because of photodissociation, photoionisation or radiation pressure, such as CO, CI, etc (Lagrange et al., 1998; Roberge et al., 2000; Brandeker et al., 2004; Nilsson et al., 2012; see Figure 2d). In any case, the total amount of gas in the β Pic system is significantly smaller than that around younger (a few Myr) systems such as Herbig stars or T Tauri stars, in agreement with the estimations of primordial disc dissipation timescales of about 3–6 Myr.

Early indications of planets in the β Pic system

The presence of planets in the β Pic disc had been suspected since the 1990s from several independent considerations:

- The mere presence of short-lived dust, produced by destruction (collision, evaporation) of kilometre-sized bodies indicated that at least the building blocks of planets were already present in the system. The gravitational perturbation of a giant planet on cometary-like bodies was found to be the best explanation for the observed rate of comet infall. Dedicated simulations concluded that such a planet (a giant planet) should be located within 10 au of the star (Beust & Morbidelli, 2000).
- The presence of a relative void of material in the inner parts of the disc was also attributed to the sweeping up of material by planets. This generic mechanism has also been invoked in other instances, but no dedicated modelling has been done to our knowledge for the β Pic disc.
- Photometric data recorded at the Swiss telescope in the early eighties on β Pic (which used to be regarded as a photometric standard) were re-analysed in the nineties and revealed that intriguing variations had occurred on 10 November 1981. Explanations involving either a multiple giant cometary tail or a transiting planet were proposed to account for the observed variations (Lecavelier et al. [1997] and references therein);
- Thermal infrared data show inhomogeneities in the disc: belt-like structures or clumps that could be due to sculpting by planets located in the gaps (see Freistetter [2007] for more detail). In particular, the latter, a 2–5 Jupiter mass planet at about 10 au, was proposed by Freistetter (2007);
- In the late 1990s the Hubble Space Telescope (HST) and ESO 3.6-metre Adonis adaptive optics high spatial resolution data at optical/near-IR wave-

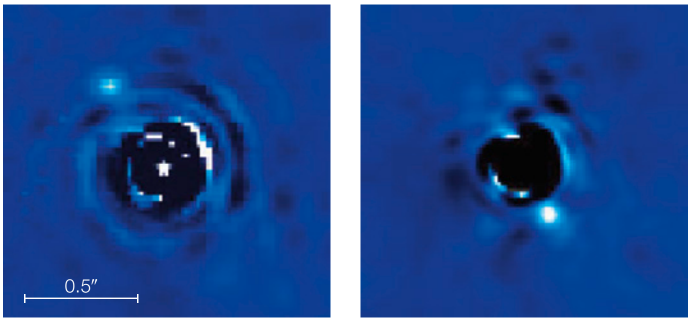


Figure 3. NACO L'-band images of β Pic b are shown: in 2003 (left) with star-planet separation ~ 400 milliarcseconds; in 2009 (right) with separation ~ 300 milliarcseconds. From Lagrange et al. (2009; 2010).

lengths revealed the presence of an inner warp in the scattered-light images, extending up to a few tens of au (Burrows et al., 1995; Mouillet et al., 1997). Dynamical simulations allowed us to show that a massive companion on a slightly inclined orbit with respect to the outer disc midplane could explain the warp, provided its mass (*M*) and separation (*a*) fulfilled a constraint on $M \times a^2$ (Mouillet et al., 1997; Augereau et al., 2001).

None of these considerations proved that planets were indeed present, however altogether they formed a very indicative set of clues.

A giant planet at about 9 au

Using NACO on the VLT, we detected a faint source about 0.4 arcseconds northeast from the star, roughly along the disc direction, in data taken in November 2003 (Lagrange et al., 2009, see Figure 3). Its apparent magnitude of $L' \approx 11.2$ indicated that, if bound to the star, it had a temperature of ~ 1500 K and a mass of about 8 $M_{Jupiter}$ according to the hot-start planet models from the Lyon group (Baraffe, 2003). We had to wait until autumn 2009 to see this object again, this time 0.3 arcseconds southwest from the star and to confirm that it was indeed bound to the star (Lagrange et al., 2010). In the meantime, the companion had travelled about half an orbit behind the star. Subsequent NACO monitoring allowed us to resolve the orbit of β Pic b (Chauvin et al., 2012) and constrain the semi-major axis of the planetary orbit to the range 8–12 au, most probably at 8–9 au, that is within the orbit of Saturn in the Solar System (Figure 4). β Pic b is then located in the region where, according to current formation models, and given the star age and mass, giant planets can have formed *in situ* by core accretion, like the giant planets of the

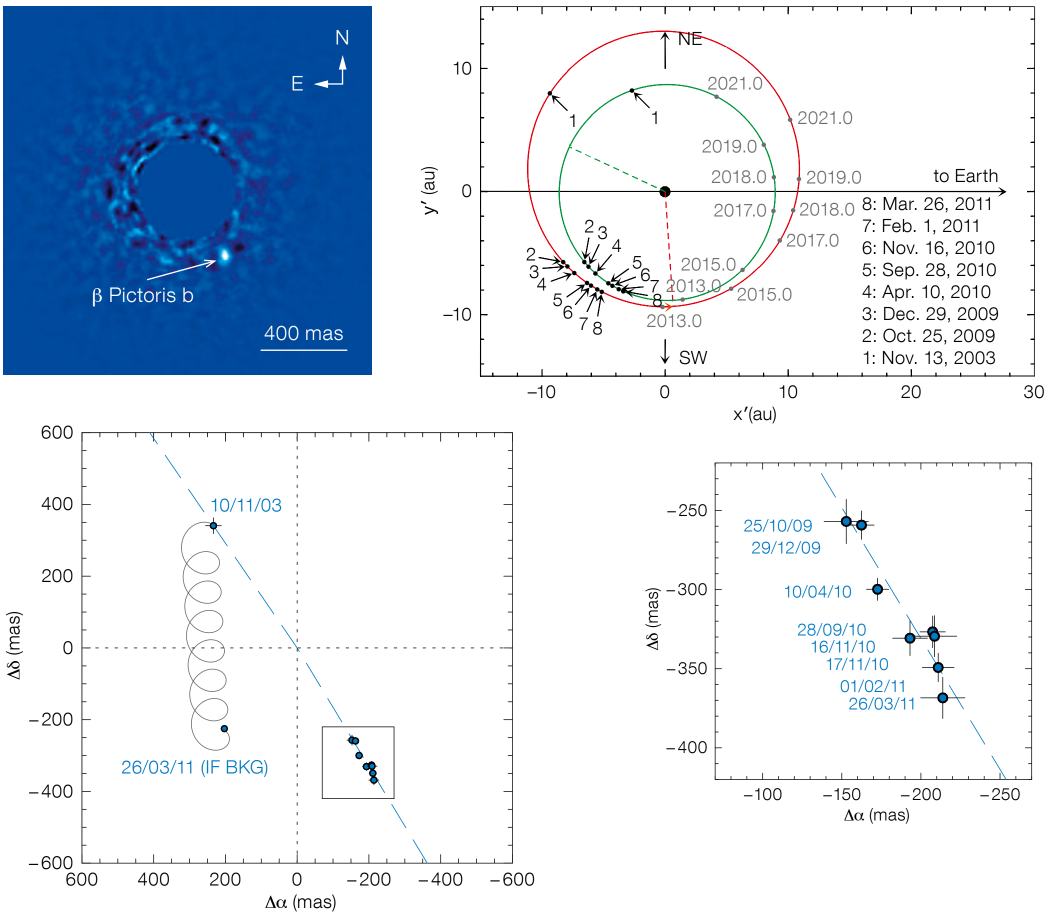


Figure 4. *Ks*-band Image of β Pic b in April 2010 (from Bonnefoy et al., 2011) is shown (upper left). The astrometric monitoring of β Pic b relative to β Pic is reported in the lower plots. The predictions for the position of β Pic b in case of a background source are reported in gray from 10 November 2003 to 26 March 2011 (lower left). A zoomed view of the most recent astrometric observations over 2010 and 2011 is presented at lower right. At upper right, details of the orbit of β Pic b from Chauvin et al. (2012) for two possible solutions of low (e = 0 in green) and slightly higher eccentricity (e = 0.16 in red) are illustrated.

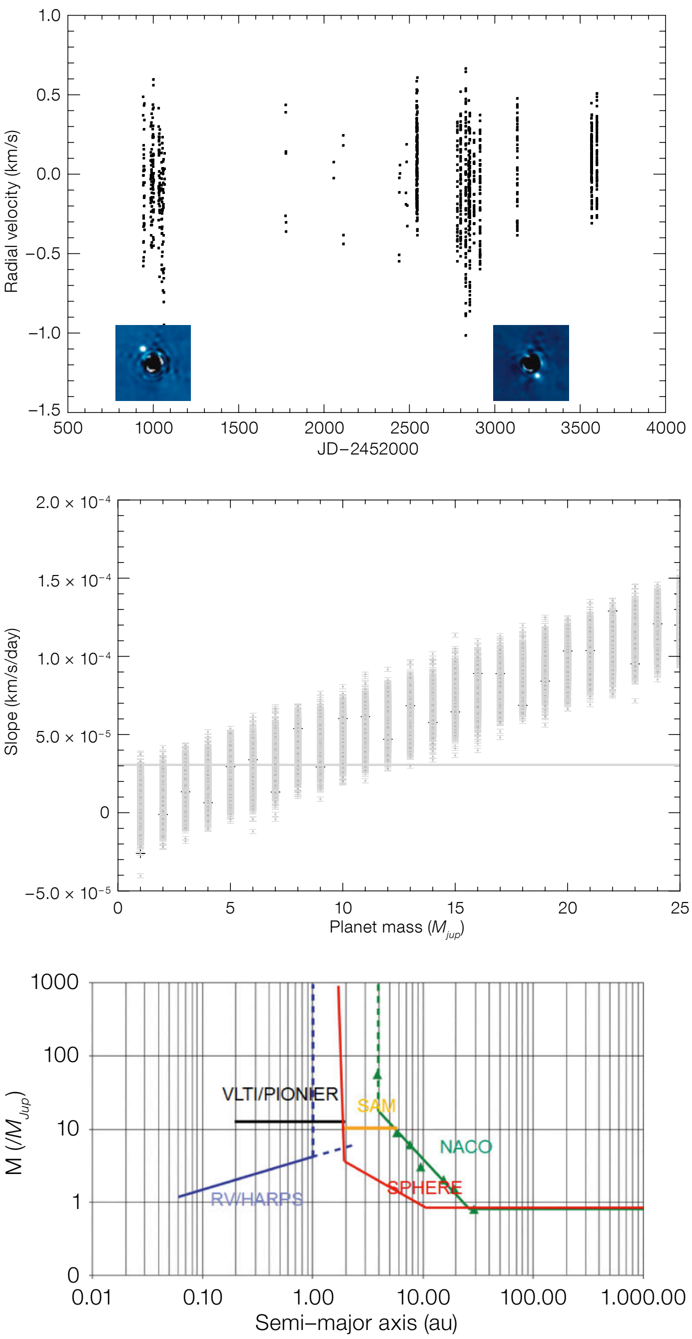


Figure 5. Upper: Radial velocity variations of β Pic (from Lagrange et al., 2012a) observed with ESO 3.6-metre and HARPS are plotted together with the NACO images of β Pic b. Centre: Slope of the radial velocity induced by a planet of different masses with a 7400-day period, similar to that of β Pic b, when using the available data sampling; the horizontal lines indicate the upper level of the slope (3 σ) derived from β Pic radial velocity data. For each mass, the various points correspond to different noise realisations. Lower: Current detection limits in the β Pic system, coupling data from different instruments, especially HARPS, VLT adaptive optics and VLTI Pionier, and showing the potential role of the forthcoming VLT instrument SPHERE.

Solar System, rather than by disc gravitational instability (the latter mechanism being rather inefficient at a few au).

Further imaging at *Ks* (Bonnefoy et al., 2011; see Figure 4) and at 4.0 μm (Quanz et al., 2010) led to mass estimates for β Pic b similar to those deduced from *L′*-band data, again using the hot-start models (Baraffe, 2003). It has to be stressed that the mass determination of β Pic b, as well as those of all other imaged planets, relies on model-dependent brightness–mass relationships. So far, the hot-start models have been used; they assume that the giant planet is formed by the collapse of a gaseous cloud and that the energy released from accretion is entirely converted into heat. The young planet is therefore still quite hot during its first 100 Myr, and within the reach of detection by current/forthcoming imagers, whereas more mature (and colder) counterparts would not be so easily detected. Whether these hot-start models could apply to planets formed by core accretion is obviously questionable.

A first attempt to model core accretion was made by Marley et al. (2007), assuming significant loss of energy during the accretion shock of the gas onto the planet core. This resulted in initial internal entropies much lower than assumed so far and, consequently cooler young giant planets, much less luminous at young ages. However, according to this model, all 12-Myr-old giant planets would be much fainter than β Pic b. Recent, more detailed studies (Mordasini et al., 2012; priv. com.) indicate that the observed luminosity of β Pic b could be compatible with a planet formed with small energy loss during this gas accretion shock. Clearly, current evolutionary models to predict the properties of giant planets still need some tuning; they also need calibrations, i.e. measurements of planet fluxes and independent (astrometric, velocimetric) measurements of their masses. To possibly constrain the mass of β Pic b, we analysed high precision HARPS data collected over eight years since 2003 (Figure 5, top panel) and found that the dynamical mass of β Pic b is less than 10, 12 and 15.5 M_{Jup} if orbiting at 8, 9 and 10 au respectively (Lagrange et al., 2012a). These results illustrate how crucial the combination of radial velocity data and direct imaging might be.

Disc–planet interaction

A subsequent question is whether the β Pic b planet can explain the characteristics of the disc morphology and, in particular, its inner warp. Using the constraints derived from our 2001 dynamical studies, and taking into account the updated mass and age of the system, we found that indeed it could, provided it orbited on a slightly inclined orbit. We recorded new data in which the disc and the planet could be seen simultaneously (to minimise astrometric uncertainties) and that allowed us to conclude that the planet is not orbiting in the plane of the outer disc, but most probably in the warped part of the disc (Lagrange et al., 2012b). Finally, order of scale considerations show that β Pic b could also be responsible for the FEBs at the origin of the replenishment of the disc gas phase, but new modelling is still needed to ascertain this point.

Future work

An unprecedented set of data has been gathered on the β Pic system over some 28 years and remains unique in several aspects. The disc provides the opportunity to study, in great detail, the physical and chemical characteristics of sites of ongoing, or recently completed, planetary formation. Knowledge of the system has improved a lot, but at the same time many questions are still unanswered. What is the origin of the stable gas in the system? What do the dust and gas tell us about planet formation? In that context, a very valuable piece of information is also expected from ALMA, as indicated by the spectacular (yet uncalibrated) test image. How did β Pic b form? Are there other planets in the system, as expected if the observed dust rings/clumps are indeed due to planets? Our exploration of the planet content will significantly improve in the future thanks to forthcoming VLT/SPHERE and Gemini/Gemini Planet Imager high resolution instruments, and to the combination of the results with radial velocity or astrometric data (see Figure 5, bottom panel).

β Pic among other debris discs

β Pic is, so far, the most studied example of the debris discs. Such discs are favourable places to search for planets, especially those around young stars, such as β Pic, as the planets are expected to be brighter than their older counterparts and, unlike younger systems, most of the primordial material has been expelled, or has accreted into planets, and therefore does not set a limit on planet detection. Discs with peculiar structures such as rings with sharp edges or asymmetries and spirals, possibly shaped by planets, are thought to be even more interesting targets, even though we know that other physical effects not involving planets can also lead to the formation of such structures (Takeuchi & Artymowicz, 2001; Lyra & Kuchner, 2012). It is remarkable however that all the stars (as yet only three examples are known) around which relatively close (≤ 120 au) planets have been imaged are surrounded by debris discs: Fomalhaut (Kalas et al., 2008); HR8799 (Marois et al., 2010) and β Pictoris. Thanks to instruments offering increased spatial resolution and/or sensitivities (VLT/SPHERE, the European Extremely Large Telescope and the James Webb Space Telescope), planet searches will become possible for an increasing number of targets, allowing a wider exploration of the diversity of planetary systems and their formation processes.

References

Augereau, J. C. et al. 2001, A&A, 370, 447
Aumann, H. H. 1984, BAAS, 16, 483
Baraffe, I. et al. 2003, A&A, 402, 701
Beust, H. et al. 1990, A&A, 236, 202
Beust, H. & Morbidelli, A. 2000, Icarus, 143, 170
Bonnefoy, M. et al. 2011, A&A, 528, L15
Brandeker, A. et al. 2004, A&A, 413, 681
Burrows, C. J., Krist, J. E. & Stapelfeldt, K. R. 1995, AAS, 187, 3205
Chauvin, G. et al. 2012, A&A, 542, 41
Freistetter, F., Krivov, A. V. & Löhne, T. 2007, A&A, 466, 389
Hobbs, L. M. et al. 1985, APJ, 298, 357
Kalas, P. et al. 2008, Science, 322, 1345
Lagage, P. O. & Pantin, E. 1994, Nature, 369, 628
Lagrange-Henri, A. M., Vidal-Madjar, A. & Ferlet, R. 1988, A&A, 190, 275
Lagrange, A.-M. et al. 1998, A&A, 330, 1091
Lagrange, A.-M., Backman, D. & Artymowicz, P. 2000, in PPiv, Univ. of Arizona Press, 639
Lagrange, A.-M. et al. 2009, A&A, 493, L21
Lagrange, A.-M. et al. 2010, Science, 329, L57
Lagrange, A.-M. et al. 2012a, A&A, 542, 40L
Lagrange, A.-M. et al. 2012b, A&A, 542, 18
Lecavelier Des Etangs, A. et al. 1997, A&A, 328, 313
Lyra, W. & Kuchner, M. J. 2012, arXiv1204.6322L
Marley, M. S. et al. 2007, ApJ, 655, 541
Marois, C. et al. 2010, Nature, 468, 1080
Mouillet, D. et al. 1997, MNRAS, 292, 896
Nelson, R. P., Lagrange, A.-M. et al. 2001, A&A, 370, 447
Nilsson, R. et al. A&A, 544, 134
Quanz, S. P. et al. 2010, ApJ, 722, 49
Roberge, A. et al. 2000, 538, 904
Smith, B. & Terrile, R. 1984, Science, 226, 1421
Takeuchi, T. & Artymowicz, P. 2001, ApJ, 557, 990
Telesco, C. M. et al. 2005, Nature, 433, 133
Vidal-Madjar, A. et al. 1986, A&A, 167, 325
Wilner, D. J., Andrews, S. M. & Hughes, A. M. 2011, ApJ, 727, 42

Image of the Galactic H II region Sharpless 2-292 (also known as RCW 2 and Gum 1) taken with the MPG/ESO 2.2-metre telecope and the Wide Field Imager. The main source of ionisation of the nebula is the central bright Be star HD 53367. The ionised gas is visible in Hα emission and other filters of this composite image were *B*, *V* and *R*. Further details can be found in Release eso1237.