Observation of the Central Part of the β Pictoris Disk with an Anti-Blooming CCD

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1. The β Pictoris Disk

Since the discovery with the IRAS Satellite of a number of main-sequence stars which show an infrared excess, direct imaging has proved, in the only case of the southern A5-type star β Pictoris, that this excess is caused by a disk of dust surrounding the star (Smith and Terrile, 1984). The favourable orientation of the disk, viewed nearly edge-on from Earth, has permitted the further detection of its gaseous counterpart, with a typical density n(H) ~ 10^5cm^{-3} (Hobbs et al., 1985; Kondo and Bruhweiler, 1985; Vidal-Madjar et al., 1986). Subsequent observations have emphasized the complex time variations of the circumstellar (CS) lines, both in the visible and the UV (Ferlet, Hobbs and Vidal-Madjar, 1987; Lagrange, Ferlet and Vidal-Madjar, 1987).

In order to interpret the extensive data set gathered on the β Pictoris protoplanetary system, we have proposed a model in which the sporadic redshifted events are the result of the evaporation in the vicinity of the star of solid comet-like bodies falling into the star (Lagrange-Henri, Vidal-Madjar and Ferlet, 1988; Beust et al., 1989). Numerical simulations of infalling bodies which evaporate when grazing the star are able to reproduce the observational data and provide constraints on the bodies' nearly parabolic orbits: for instance, a specific direction of the orbit's axis with respect to the line of sight is required, along with close perihelia ≥ 10 stellar radii. We then came to the conclusion that the numerous events seen could be due to the presence of a giant planet (or proto-planet) in the β Pictoris disk which perturbs a lot of small passing-by objects and throws some of them towards the star (see e.g. Beust, Vidal-Madjar and Ferlet, 1991, and references therein), thus possibly clearing up the inner part of the disk.

From their coronographic study, Smith and Terrile (1984) have shown that an $r^{-4.3}$ power law was well representing the dust distribution within the disk. However, at less than 6 arcsec from the star (100 AU), i.e. behind the coronographic mask, they showed that if this law was extrapolated to less than 30 AU, a too strong extinction of the direct starlight (passing through the edge-on disk) would result. Therefore, they claimed that a cleared-up region was probably present within 30 AU from the star, possibly due to planetary formation. Later on, Diner and Appleby (1986), using the same coronographic data but coupled with the IRAS observations, produced a disk model coherent with both dust scattering and emissivity, and found that within 100 AU no strong constraint was present in the data: dust distributions presenting very small cleared-out inner regions were certainly acceptable. This is due to the fact that, similarly to the coronographic observations, the low resolution IRAS data are sensitive to relatively cool (outer and extended) dust. Then, Artymowicz, Burrows and Paresce (1989), using new coronographic data (Paresce and Burrows, 1987) still limited to more than 6 arcsec from the star, along with the IRAS data, confirmed the radial power law (although slightly less steep, in $r^{-3.6}$) and the Diner and Appleby (1986) conclusions, i.e. a 5 to 15 AU cleared inner region is compatible with the observations.

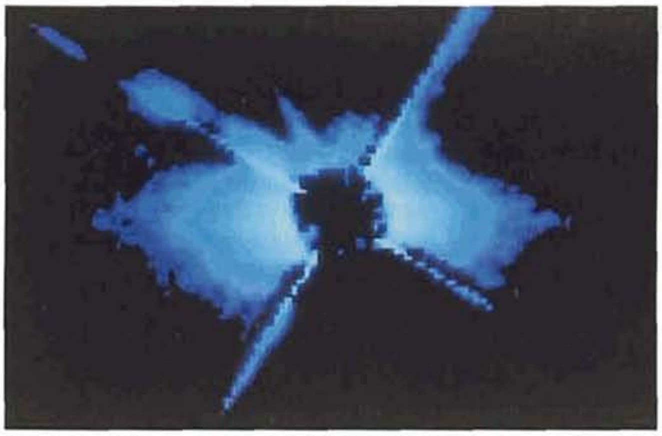

Figure 1a: *20-sec exposure (V filter) of β Pictoris corrected for the diffuse light level by the use of a template star (see text). The bright spikes due to the secondary spider cannot be completely corrected, but do not perturb disk brightness evaluations due to their angular separation.*

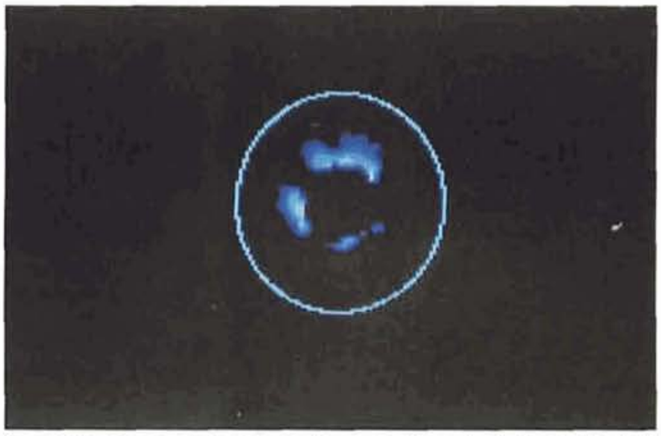

Figure 1b: *Same correction made on another star (with similar light levels) obviously shows no circumstellar disk. A 6-arcsec-radius circle is drawn around the star to visualize the limit of previous coronographic observations.*

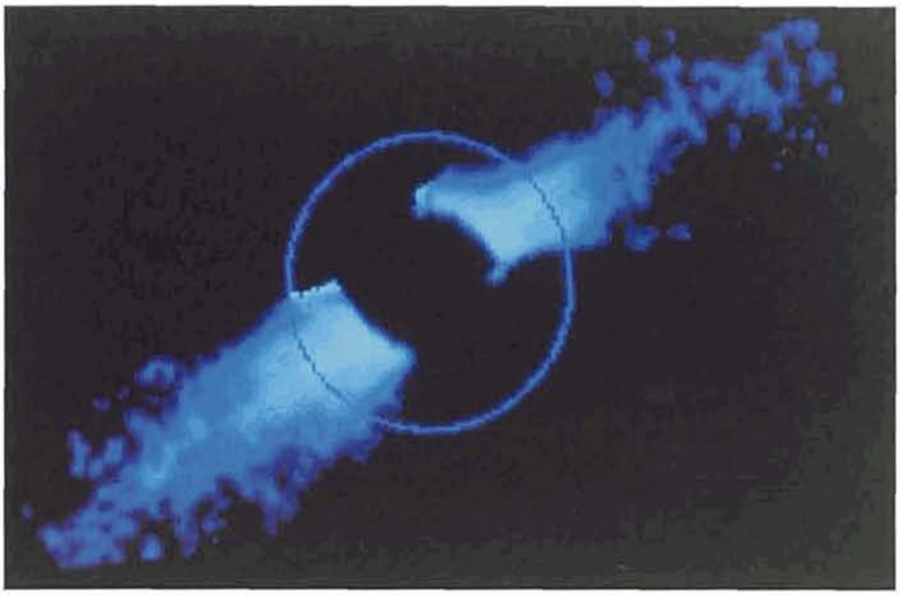

Figure 2: *The β Pictoris disk image without the spikes, radially flattened to strengthen the weakest parts of the disk. North is up. A 6-arcsec-radius circle is drawn. This disk is clearly seen down to 2.5 arcsec from the star. Shorter exposures reveal the disk down to 2 arcsec (30 AU).*

Simultaneously, Telesco et al. (1988), completing 10 and 20μ ground-based observations with 5 arcsec resolution, were able to constrain more strongly the different models: the β Pictoris inner disk is relatively clear of dust, possibly up to 50 AU (3 arcsec from the star). However, more recent observations from 8 to 12μ by Telesco and Knacke (1991) led to a possible detection of a spectral signature related to silicates, but only seen within 3 arcsec from the star.

From all these observations, it is plausible to assume that a dust-free zone exists in the inner regions of the β Pictoris disk.

Observations with an Anti-Blooming CCD

To observe the disk closer to the star, we decided to use an anti-blooming CCD (THX 7852), instead of a classical one associated to a coronographic approach. In effect, all the observations published with coronographs give very good results far from the star (Smith and Terrile, 1984; Paresce and Burrows, 1987), but fail close to it, the limit being around 6 arcseconds. The difficulty to get closer is due to the diffuse light around the mask which is extremely sensitive to the star position behind the mask, a position difficult to control without any adaptive optical device. Fluctuations producing unrepeatable changes of diffuse light levels around the mask make difficult to achieve quantifiable observations with such techniques very close to the star.

On the contrary, the use of an anti-blooming CCD which avoids the contamination of pixels adjacent to saturated ones, allows the direct observation of the disk next to the star without the use of any coronograph. Stellar light simply saturates some pixels while the nearby ones collect charges related to the light coming from the vicinity of the star. This technique was well developed in planetary studies by Colas (1991), and led to the detection of very faint satellites ($V \sim 16$) near the giant planets.

The size of the stellar image is thus simply defined by the seeing and the exposure time. Typical values are between one and two arcseconds, representing roughly the limit of that observational approach. Use of adaptive optics could further reduce the effect of the seeing, and observations of the disk at less than one arcsecond from the star should become possible. The limitation is then only due to the diffuse light characteristics in the telescope, produced by both the cleanliness of the mirrors and the induced diffraction pattern.

The recorded images with such a CCD must be simply centred on the stellar images in order to give the possibility to either add them and improve S/N by selecting sharp images (always corresponding to shorter exposures), or correct for the diffuse light effect within the telescope by subtracting the properly centred images of a template star which was in our case the nearby star α Pictoris.

The observations were performed in October 1991, at the 2.2-m Telescope at La Silla. To probe the disk at different distances, series of images were taken with exposure times ranging from 0.5 s (to see as close as possible to the star) to 300 s (to detect the disk as far as possible and have an overlap with the previous coronographic images). This has been done with the four standard filters: B (440 nm), V (550 nm), R (700 nm) and Ic (800 nm). More than 450 CCD images were taken, and an average of 10 was gathered for each filter and exposure time. Additional exposures were recorded with different angular position of the bonette in order to test the effect of the CCD orientation relative to the disk. No changes were observed.

Data Analysis

After the classical bias and flat fielding corrections of the CCD frames (see e.g. Buil, 1989), one of the difficulties was to properly correct for the diffuse light level by using the template star, observed almost simultaneously with the same instrument setting. This correction was done by scaling properly the diffuse light level of one star relative to the other in the two quadrants where the disk is not observed. This is not a simple linear correction. The radial variation of the correction factor was evaluated assuming, in a first approximation, that the diffuse light (away from the obvious spikes due to the telescope spider) presents a circular symmetry.

The result is shown in Figure 1a, in which the image was rotated in order to have the disk horizontal. The disk detection is obvious, particularly when comparing with Figure 1b in which the same correction was applied to another template star with no disk at all, and in which all light levels are at most equal to 10% of the ones in Figure 1a, at similar angular distances from the central stars. It is also very clear in Figure 1 that the correction process is unable to perfectly eliminate the very bright spikes in the case of β Pictoris because they are partly due to scattered light from the disk itself.

The final image of the β Pictoris disk is shown in Figure 2, where the brighter spikes were simply taken out, and the disk luminosity is flattened by an r^{-3} power law in order to better illustrate its radial extent. The superimposed circle represents a region of 100 AU (6 arcsec) around the star, corresponding to the inner limit of the coronographic studies. The disk is seen down to 2.5 arcsec from the star. Shorter exposures allow a precise evaluation of the disk brightness down to 1.8 arcsec, i.e. down to less than 30 AU.

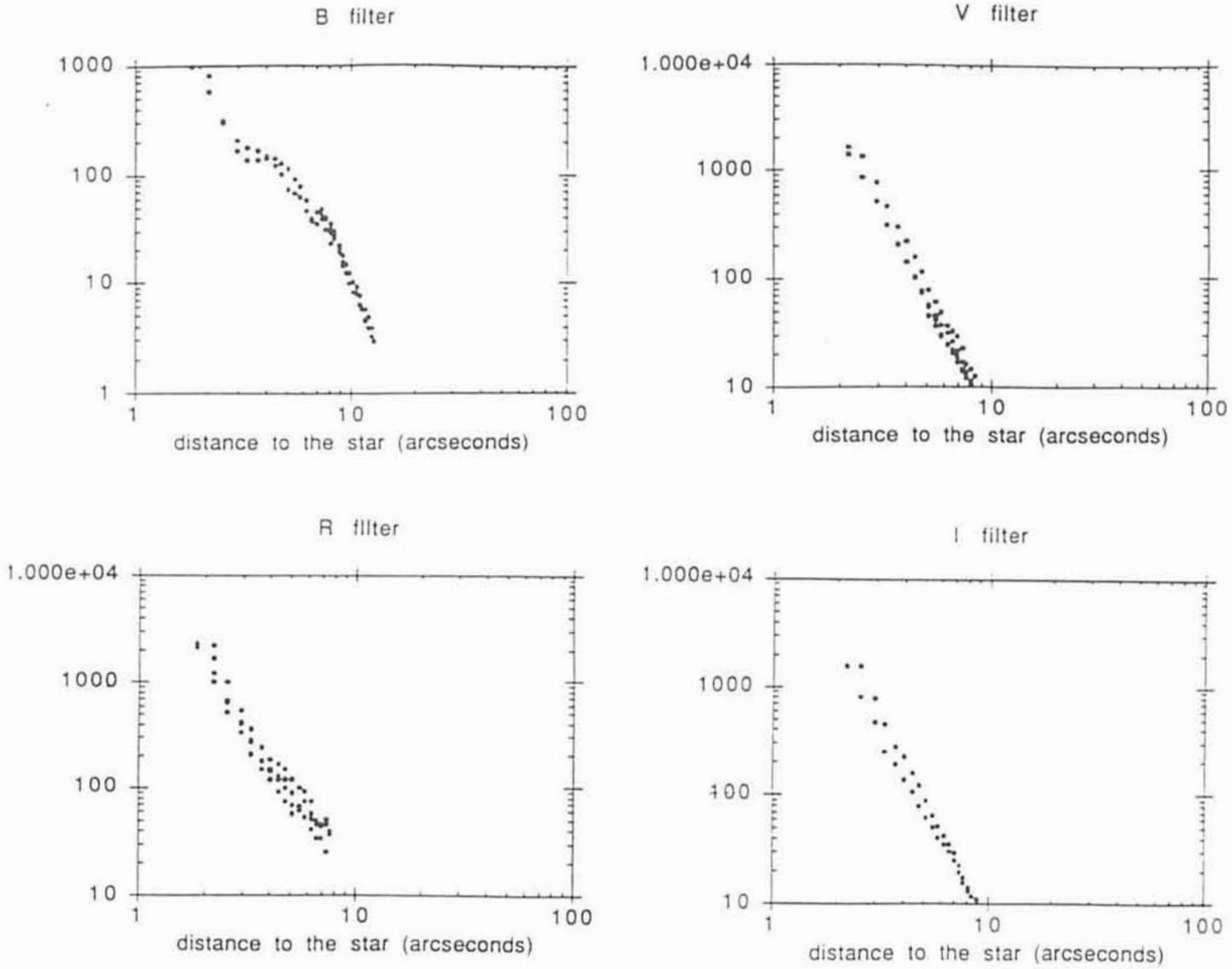

Figure 3: *Disk brightness in arbitrary units for the four filters as a function of the stellar distance in arcsec. In V, R, and Ic filters, an $r^{-3.6}$ power law is found, while in the B filter, departure from this power law is clearly detected at less than 5 arcsec from the star (60 AU).*

Preliminary Results

From these different images, it is possible to reconstruct the disk brightness between 2 and 12 arcsec by evaluating the total signal above background perpendicular to the disk plane. The results for the different filters are shown in Figure 3. Nearly an $r^{-3.6}$ power law is found in V, R and Ic, in excellent agreement with the previous observations of Artymowicz, Burrows and Parasce (1989).

The striking difference is seen in the B filter. The power law found at more than 6 arcsec from the star matches very well the one found in the other filters and confirms also the previous coronographic results: the disk colour does not vary with the distance to the star. Furthermore, these disk colours are shown in Figure 4 after normalization with the stellar colours themselves. Our result thus confirms the flat albedo of the dust particles, demonstrating again the probable large size of the grains present in the outer disk (> 1 μ).

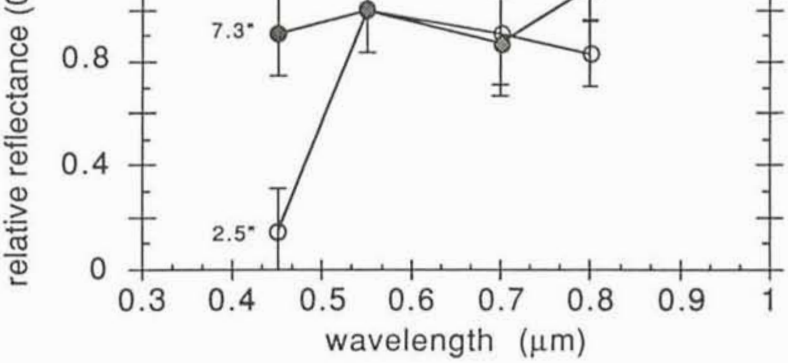

Figure 4: *The disk colour is given at two different locations in the disk and in the four filters (after normalization with the stellar light). Neutral colour is seen at large distances, while a drop in the B filter is clearly observed in the inner regions.*

However, at shorter distances from the star, we observe a very clear drop in the B filter, showing that the dust albedo seems to decrease by at least a factor of 4 when moving from 7.3 arcsec to 2.5 arcsec. This slow drop of the B albedo is also clearly seen in Figure 3.

This is an extremely interesting and totally new result, which seems to indicate that the nature of the grains is changing when moving inward. More precisely, a change in the grain size could not explain such a variation because larger grains should induce no colour changes while smaller ones should, on the contrary, favour the blue. However, a change in surface albedo of the grains could easily explain such a behaviour; from material albedoes by Gaffey and McCord (1979), a similar behaviour could be found in icy material more and more covered with dust.

If this explanation is correct, it seems to indicate that the grains in the β Pictoris disk are ices more and more dusty when going inward. This might be a first direct indication that a different situation prevails in the inner regions of the disk, namely at less than about 75 AU (5 arcsec), where planets are possibly forming.

We also have confirmed a slight asymmetry in the disk from one side to the other, but noticed an inversion of that asymmetry in the inner regions, leading to an average symmetric disk. This may again be the signature of planetary formation processes within the β Pictoris disk.

Conclusions

We have shown that a new observational approach does exist to look for very faint features near bright objects. Compared to classical stellar coronography, it allows observations closer to the star, particularly if quantitative results must be reached very close to it.

In the case of the β Pictoris disk, we confirmed previous results obtained at more than 6 arcsec from the star. Moreover, we were able to directly observe the disk down to 2 arcsec. The main results are:

- the disk extension continues down to 30 AU from the star, following an $r^{-3.6}$ power law;
- the disk colour is neutral in V, R and Ic at all observed distances;
- the disk colour drops down in the blue (B) when going inward, starting at about 75 AU from the star, to reach a factor of 4 reduction at 30 AU;
- a slight disk asymmetry (80%) is present, but is inverted within 100 AU from the star.

Obviously, this technique is very promising and a lot more is still to be done to further confirm these results and observe the disk even closer. From our first approach we are convinced that observing the β Pictoris disk down to less than one arcsec from the star is within the possibilities. Furthermore, this is potentially a very powerful technique to search for other protoplanetary disks around nearby stars, even if they are more inclined, as the β Pictoris one is still a unique phenomenon.

References

Artymowicz, P., C. Burrows, and F. Paresce, *Astrophys. J.*, **337**, 494, 1989.

Beust, H., A.M. Lagrange-Henri, A. Vidal-Madjar, and R. Ferlet, *Astron. Astrophys*, **223,** 304, 1989.

Beust, H., A. Vidal-Madjar, and R. Ferlet, *Astron. Astrophys.*, **247,** 505, 1991.

Buil, C., in *Astronomie CCD*, ed. S.A.P., 1989.

Colas, F., *University of Paris*, Ph.D. Thesis, 1991.

Colas, F., and J.E. Arlot, *Astron. Astrophys.*, **252,** 402, 1991.

Diner, D.J., and J.F. Appleby, *Nature*, **322,** 436, 1986.

Ferlet, R., L.M. Hobbs, and A. Vidal-Madjar, *Astron. Astrophys.*, **185,** 267, 1987.

Gaffey, M.J., and T.B. McCord, in *Asteroids*, **688,** ed. T. Gehrels, 1979.

Hobbs, L.M., A. Vidal-Madjar, R. Ferlet, C.E. Albert, and C. Gry, *Ap. J. Lett.*, **293,** L29, 1985.

Kondo, Y., and F.C. Bruhweiler, *Ap. J. Lett.*, **291,** L1, 1985.

Lagrange, A.M., R. Ferlet, and A. Vidal-Madjar, *Astron. Astrophys.*, **173,** 289, 1987.

Lagrange-Henri, A.M., A. Vidal-Madjar, and R. Ferlet, *Astron. Astrophys.*, **190,** 275, 1988.

Paresce, F., and C. Burrows, *Ap. J. Lett.*, **319,** L23, 1987.

Smith, B.A., and R.J. Terrile, *Science*, **226,** 1421, 1984.

Telesco, C.M., E.E. Becklin, R.D. Wolstencroft, and R. Decher, *Nature*, **335,** 51, 1988.

Telesco, C.M., and R.F. Knacke, *Ap. J. Lett.*, **372,** L29, 1991.

Vidal-Madjar, A., L.M. Hobbs, R. Ferlet, C. Gry and C.E. Albert, *Astron. Astrophys.*, **167,** 325, 1986.

Spectroscopy of Arcs and Arclets in Rich Clusters of Galaxies

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1. Introduction

Since 1987, the redshift determination of the giant arcs observed in rich clusters of galaxies has been a great challenge for observers, as it was initially the only way to confirm the nature of the gravitational phenomenon. But the faint surface brightness of most of the arcs, only slightly compensated by the extension of the image, is partly responsible for the slow progress of such observations although their scientific impact is quite large.

Let us begin this paper with some chronological steps in the discovery and the observations of giant luminous arcs. The first main result, about one year after the discovery of giant arcs in two clusters of galaxies (Soucail et al. 1987, Lynds and Petrosian 1986), was the redshift measurement of the giant arc in Abell 370, a rich cluster at a redshift of 0.37. A strong emission line was detected all along the structure, with a curved slit punched with the PUMA system installed at the 3.6-m at La Silla. The line was immediately identified with the well-known [OII] line at 3727 Å, redshifted at 0.725. This important result was the confirmation of the hypothesis that we were observing a gravitationally distorted image of a background source through the cluster of galaxies. One year later we continued our study by showing that many clusters were acting as giant lenses on the numerous population of faint blue galaxies detected at the same period by Tyson (1988). For example in A370, many weakly distorted blue objects were detected, with an orthoradial orientation with respect to the cluster centre (Fort et al. 1988). These so-called "arclets" were also supposed to be images of distant background galaxies. But in this case, the confirmation of this