On the Nature of the Beta Pictoris Circumstellar Nebula

*Francesco Paresce** and *Pawel Artymowicz*

Space Telescope Science Institute
3700 San Martin Drive
Baltimore, Maryland 21218 U.S.A.

Summary

We summarize the observed properties and deduced physical characteristics of the Beta Pictoris circumstellar nebula obtained from a detailed analysis of existing IR and optical data. On the basis of these results, we reject the hypothesis that the observed feature is a bipolar nebula surrounding an evolved star. We claim the nebula is a flattened disk of orbiting particles making up a planetary system in its clearing out phase as small grains collide, erode, and are swept out by radiation pressure.

Introduction

The nearby A5V star Beta Pictoris (HR2020) has attracted some attention lately due to the discovery of a spatially resolved IR excess (Gillett, 1986) and a thin extended bipolar reflection nebulosity in the near IR and optical (Smith and Terrile, 1984, 1987; Paresce and Burrows, 1987). There are several possible *a priori* explanations for the observations with the most plausible being either a true bipolar nebula (BPN) as observed around evolved stars (Morris, 1981; Herbig, 1989) or a flattened disk of orbiting material in a proto or planetary system, possibly somewhat like our own. This latter possibility, of course, is, by far, the most exciting and, if confirmed, could represent an unparalleled opportunity to observe another solar system in considerable detail due to its relative proximity to the Sun. It is, consequently, quite important to be able to place this nebulosity in its proper astronomical context. In this brief report, we investigate this issue on the basis of the known facts about the system and the logical deductions that can be made therefrom.

---

* Affiliated with the Astrophysics Division of the Space Science Department of ESA.

https://doi.org/10.1017/S0252921100023770 Published online by Cambridge University Press

Physical Characteristics of the Beta Pic Nebulosity

The basic question, then, is: what is the elongated feature at p.a. 30° shown in figure 1? This image was taken by Paresce and Burrows with their coronograph at the ESO 2.2m telescope in the Ic band centered at 7900Å. The spacing of the isophote contours in this figure corresponds to an 0.5 magnitude surface brightness difference normalized to an intensity of 15.9 mag arcsec^{-2} in this band at 6" from the center of the star located at the intersection of the N, E axes and hidden by the 2" thick occulting wedge. This feature can be observed out to at least 1100 AU from the star with a roughly constant resolved FWHM thickness of 30 - 50 AU. The observed broad band fluxes from B to I_c are consistent with scattering of Beta Pic starlight by neutrally reflecting particles. This wavelength independent albedo and a recently discovered decrease in U band reflected light over the gray case is overwhelming evidence for large (a > 1 micron) particles as the dominant scatterers. This is not surprising since smaller particles would certainly not survive long in the Beta Pic environment before being blown out by radiation pressure (Artymowicz, 1988). The nebulosity has been reliably observed down to ≈ 5" (85 AU) from the central star, a limit set, presently, by the seeing dominated profile of the V = 3.87 central object.

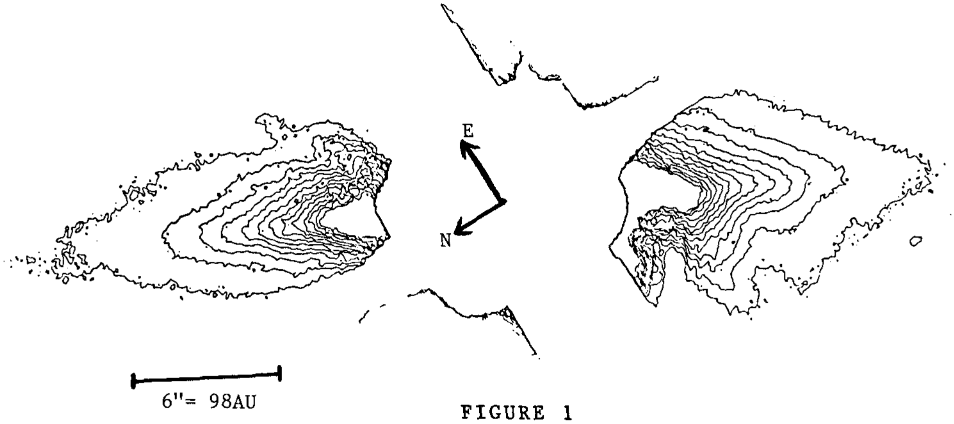

FIGURE 1

The Beta Pic system exhibits the largest excess far IR flux of any main sequence star observed by IRAS *i.e.*, 1.59, 10.1, 18.8 and 11.2 Jy at 12, 25, 60 and 100 microns, respectively, after subtraction of a suitable photospheric component. The deconvolution of spatial IRAS scans at 60 microns yield a < 14" FWHM size in the in-scan (0° p.a.) and a nominal 22" ± 6" FWHM size in the cross-scan (70° p.a.) direction (Gillett, 1986) although a subsequent analysis (Gillett *et al.*, 1988) revised the error bar to justify only a marginal spatial IR resolution. Attempts to resolve Beta Pic in the 1 - 10 micron near IR range have been inconclusive, so far.

Beta Pictoris has been known for some time as a shell star with strong narrow absorption lines of Ca II and Na I intrinsic to the star's immediate environment

https://doi.org/10.1017/S0252921100023770 Published online by Cambridge University Press

because about one to two orders of magnitude stronger than plausibly attributable to the intervening ISM (Hobbs *et al.*, 1985; Hobbs, 1986). Temporally varying UV lines of Al, Mg and Fe are also characteristic of this system (Bruhweiler and Kondo, 1987; Lagrange-Henri *et al.*, 1989 and references therein). These observations imply a surprisingly small amount of neutral gas in the circumstellar environment ($N_{HI} \simeq 10^{20}$ atoms cm^{-2}) with a strong concentration in the very near environment ($r \simeq 1$ AU) of the star's surface. Nebular emission in the Hα line, for example, is undetectable. The most interesting aspect of these results concerns the appearance of sporadic temporal variations in the red wing of some UV absorption lines corresponding to up to ≃ 400 kms^{-1} infall velocities. These data are presently best explained as being due to km-sized bodies, possibly comets, breaking up and evaporating as they collide with the star and temporarily populating a narrow inner region with inward spiralling gaseous debris. Since this is a well documented phenomenon in our own system (see Morrison and Owen, 1988 p. 116 for example) such an explanation does not seem as far-fetched as it may sound. The implied mass flow rate is small ($\simeq 10^{16}$ g yr^{-1}) and, thus, does not affect the stability or lifetime of a possible outer disk.

There is certainly enough observational data available on this object to make it worthwhile to attempt to construct a comprehensive model of the nebulosity. This should be possible even though the IR and optical data refer to somewhat different regions with a small but significant overlap (Norman and Paresce, 1989). Past use of oversimplified *ad hoc* models addressing only a subset of the data base has resulted in apparent contradictions and inconsistencies. We believe that a better approach is to develop self-consistent, physically realistic models of the Beta Pic nebulosity that satisfy both the optical and the IR results preferably with a single population of scattering and emitting grains. We have described in detail how a family of just such models can be found using non parametric maximum entropy techniques (Artymowicz, Burrows, and Paresce, 1989). Although a specific model depends mainly on the precise IR grain emissivity law which has to be assumed to be of the standard form $\varepsilon \sim \lambda^{-1}$, a very reasonable range of input parameters yields very similar final results. These are: a clear dust-free zone around the star of radius 10 - 20 AU with a peak dust density located at 20 - 40 AU at a grain temperature of ≃ 95 K (165K at the edge of the clear zone), a normal optical thickness at peak of $\simeq 10^{-2}$, an equivalent scattering area of $10^{30} cm^2$, and a minimum grain albedo of 0.5. An absolute minimum total mass of grains is 10^{26}g if all the mass is in 1 micron diameter particles, the minimum size allowed by the observations. A more realistic order of magnitude estimate of the nebular mass can be made by using the solar system meteoroid $a^{-3.5}$ da distribution and a particle size upper limit of 0.1 km. In this case, one obtains 10^{30} g, a value remarkably similar to the total mass of solids in our solar system. We emphasize here that all these results are basically independent of the 3 dimensional geometry assumed for the Beta Pic nebula.

https://doi.org/10.1017/S0252921100023770 Published online by Cambridge University Press

The True Nature of the Beta Pic Nebulosity

At this point, we can make some progress in sorting out the crucial question of whether the scattering and emitting material is distributed as a flattened edge-on disk reminiscent of an orbiting planetary system or, as Herbig (1989) has recently suggested, as a narrow jet-like bipolar structure similar to those encountered in classical BPNs. In the absence of reliable information on the velocity field of the observable Beta Pic emitters, the only parameter which could settle the issue definitively, the best way to proceed is to compare the known properties of the Beta Pic nebula with the average properties of BPNs. We have used data from Morris, 1981 and Calvet and Cohen, 1978 and references therein for this comparison. The relevant data are listed in Table 1. It is quite obvious from even a cursory examination of this table that, notwithstanding the associated uncertainties, it would be difficult indeed to classify the Beta Pictoris system as a BPN. Moreover, Beta Pic falls squarely on the MS for Population I stars line on the HR diagram of 13 BPNs published by Calvet & Cohen, 1978 confirming the liminosity class V classification of this object given by Hoffleit and Jaschek, 1982 and its clean distinction from the BPN class. Actually, a more detailed examination of the typical BPN morphology usually consisting of wide ragged structures many with extended horns shows that Beta Pic would be out of place even in this respect and is morphologically much more similar to the jets emanating from young stellar objects which this object is certainly not.

Table 1. A Comparison of Physical Properties: Beta Pic vs. BPNs

Property	Beta Pictoris	Bipolar Nebulae
Size (cm)	$5 \cdot 10^{15}$	$5 \cdot 10^{17}$
Mass (g)	$10^{26} - 10^{-30}$	$10^{31} - 10^{32}$
Gas to Dust Mass Ratio	< 1	$\simeq 10^{2}$
Grain Temperature	< 250K	$\geq 10^{3}$K
Expansion Velocity (km s^{-1})	?	10 - 100
Lifetime (yr)	$\simeq 10^{8} - 10^{9}$	$10^{3} - 10^{4}$
Molecules	none	OH, CO, H_2O, PAH, etc.
Mass loss Rate of Central Star ($M_\odot$ yr^{-1})	$\simeq 0$	$10^{-6} - 10^{-4}$
Intrinsic Balmer A_V(mag)	$\simeq 0$	2 - 6
v sin i	139	?

Another way to look at this problem is to ask whether a quasi-linear dusty feature could actually be theoretically supported in the Beta Pic system as we know it if one arbitrarily stretches the boundaries of the BPN category to encompass it.

https://doi.org/10.1017/S0252921100023770 Published online by Cambridge University Press

There is, presently, enough circumstantial evidence of a dynamical nature to make this hypothesis extremely unattractive. Here, we briefly enumerate some of the most obvious difficulties. First, the optical coronographic images show a structure with roughly constant cross section out to ≃ 1000 AU. Only an unobserved and very dense ambient medium would confine a jet of outflowing grains to a rapidly narrowing solid angle. Second, since the star has an appreciable rotation velocity of $v \sin i = 139$ km s^{-1}, the jets must originate from the poles of the star and the equatorial region in our line of sight would have to contain a massive, extremely optically thick disk. This possibility is completely ruled out by the relative transparency of the Beta Pic line of sight. Third, the absence of grains hotter than about 200K in the nebula imply that the grains must form on dynamical timescales in a cold environment rather than being ejected from the hot stellar envelope. We cannot think of any plausible mechanism that could accomplish this.

Perhaps most decisive is the fact that in order to support a dynamical jet we need to invoke a stellar mass loss rate for which there is absolutely no supporting evidence. A rough minimum estimate of $\dot{M}$ is 10^{26}g per 10^3 yr, the dynamical timescale, or 10^{-10} $M_\odot$ yr^{-1}. Since this refers only to the directly observable solid grains of ~1 micron size, the total implied $\dot{M}$ is more likely to be in the range 10^{-6} - 10^{-4} $M_\odot$ yr^{-1}, values that certainly would not escape detection. We conclude on the basis of these considerations and the data shown in Table 1 that the observed Beta Pictoris nebulosity is almost certainly not a standard bipolar reflection nebula. As long as a simpler and more plausible explanation for this structure exists, we see no further benefit to be derived from pursuing this hypothesis any further.

The Evolutionary State of the Beta Pictoris Disk

Having convinced ourselves that the Beta Pic nebulosity is most likely the visible and IR manifestation of an orbiting swarm of medium to large sized particles confined to a disk of 30 - 50 AU thickness viewed nearly edge-on, it is fair to ask in what evolutionary state the system finds itself presently, and whether larger planets or planetesimals exist in the occulted inner part of the disk. Although we cannot directly observe this part, all the existing data point to an unambiguous value of the normal optical thickness $\tau \approx 10^{-2}$ at the peak of the grain density profile around 30 AU. Together with the observed disk thickness, this value implies typical grain collision frequencies of 10^{-4} years at speeds of order of ≃ 1 km s^{-1}. For these conditions, grain growth by mutual coalescence or snowballing cannot occur and the dominant effect is erosion and destruction of the larger grains. The low gas densities ensure that gas accretion is unimportant anywhere in the disk. We conclude that it is very unlikely that the system is, at present, building large bodies from the dust but is in a clearing-out phase as the larger bodies are ground down to smaller ones until they can be blown out by radiation pressure.

https://doi.org/10.1017/S0252921100023770 Published online by Cambridge University Press

There are several independent indications that the Beta Pic disk contains a whole range of particle sizes, up to cometary or even larger. The first direct evidence is provided by the sporadic infall events of km sized bodies in which a large amount of redshifted gas is seen near the star as discussed earlier. Second, the importance of gas drag on long timescales requires the disk to be heated dynamically to its observed scale height by the gravity of the embedded bodies. The mass of a typical perturber capable of stirring the system to the observed thickness (between 100 AU and 200 AU from the star) is very roughly equal to one lunar mass. Third, the efficient erosion of grains requires a large reservoir of mass to be present in the disk for it to be a relatively long lived phenomenon. We can estimate that during a plausible $\simeq 2 \cdot 10^8$ yr lifetime, the system might have lost a total mass of order 10^{29}g or $\simeq 10^{-5}$ of the star's mass and only an order of magnitude less than the expected total mass of a possible planetary system formed in the primordial Beta Pic nebula. Thus, this high erosion rate may imply that in the next few 10^8 yr the Beta Pic disk will evolve toward a less conspicuous phase cleared of much of the present solid circumstellar material, possibly leaving behind only the largest surviving bodies.

References

Artymowicz, P., 1988, *Ap. J. Lett*, **335**, L79

Artymowicz, P., *et al.*, 1989, *Ap. J.*, **337**, 494

Bruhweiler, F., and Kondo, Y., 1987 in *Physics of Be Stars*, eds. A. Slettebak and T. Snow (Cambridge U. Press; Cambridge) p. 526

Calvet, N., and Cohen, M., 1978, *M.N.R.A.S.*, **182**, 687

Gillett, F. C., 1986, in *Light on Dark Matter*, Ap. Sp. Sci. Lib., **124**, ed. F. Israel (Dordrecht: Reidel), p. 61

Gillett, F. C., *et al*, 1987, *B.A.A.S.*, **19**, 829

Herbig, G., 1989, in *The Formation and Evolution of Planetary Systems*, eds. H. A. Weaver and L. Danly (Cambridge U. Press; Cambridge), p. 296

Hobbs, L. M., *et al.*, 1985, *Ap. J. Lett.*, **239**, L29

Hobbs, L. M., 1986, *Ap. J.*, **308**, 854

Hoffleit, D., and Jaschek, C., 1982, *The Bright Star Catalogue*, (Yale U. Obs.; New Haven)

Lagrange-Henri, A. M., *et al.*, 1988, *Astr. Ap.*, **190**, 275

Morris, M., 1981, *Ap. J.*, **249**, 572

Morrison, D., and Owen, T., 1988, *The Planetary System*, (Addison-Wesley; New York), p. 116

Norman, C., and Paresce, F., 1989, in *The Formation and Evolution of Planetary Systems*, eds. H. A. Weaver and L. Danly, (Cambridge U. Press; Cambridge), p. 151

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

Smith, B. A., and Terrile, R. J., 1984, *Science*, **226**, 421

______________________________, 1987, *B.A.A.S.*, **19**, 829

https://doi.org/10.1017/S0252921100023770 Published online by Cambridge University Press