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# WIDESPREAD ATOMIC GAS EMISSION REVEALS THE ROTATION OF THE $\beta$ PICTORIS DISK[1]

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## ABSTRACT

We present high-resolution Na I D spectroscopy of the $\beta$ Pictoris disk, and the resonantly scattered sodium emission can be traced from less than 30 AU to at least 140 AU from the central star. This atomic gas is coexistent with the dust particles, suggestive of a common origin or source. The disk rotates toward us in the southwest and away from us in the northeast. The velocity pattern of the gas finally provides direct evidence that the faint linear feature seen in images of the star is a circumstellar disk in Keplerian rotation. From modeling the spatial distribution of the Na I line profiles, we determine the effective dynamical mass to be $1.40 \pm 0.05\ M_{\odot}$, which is smaller than the stellar mass, $1.75\ M_{\odot}$. We ascribe this difference to the gravity opposing the radiation pressure in the Na I lines. We argue that this is consistent with the fact that Na is nearly completely ionized throughout the disk (Na I/Na $< 10^{-4}$). The total column density of sodium gas is $N(\mathrm{Na}) = 10^{15}\ \mathrm{cm}^{-2}$.

*Subject headings:* circumstellar matter — planetary systems: protoplanetary disks — stars: individual ($\beta$ Pictoris)

## 1. INTRODUCTION

The $\beta$ Pictoris disk has been the subject of intense studies ever since it was shown to have excess emission in the thermal infrared by the *IRAS* mission (Aumann 1985). The dust particles giving rise to the infrared emission also scatter the stellar light, and coronagraphic techniques revealed an elongated structure (Smith & Terrile 1984) that recently has been extremely well characterized by means of *Hubble Space Telescope* (*HST*) observations (Heap, Lindler, & Lanz 2000). Although the general impression of these images is that of a high degree of smoothness and symmetry, Heap et al. (2000) show that the peak of the elongated scattered emission has wiggles that suggest that the inner part of the disk is tilted relative to the outer part. There is also evidence for asymmetries and structures in the radial light distribution of this inner disk. Asymmetries have also been observed in the mid-IR (Pantin, Lagage, & Artymowicz 1997).

These asymmetries and the remarkable discovery (Vidal-Madjar et al. 1994; Lagrange, Backman, & Artymowicz 2000) of comet-like bodies occasionally occulting the star and giving rise to high-velocity absorption lines reveal dynamical activity that generally is interpreted as evidence for planetary disturbances (Artymowicz 1997; Augereau et al. 2001).

When it comes to the gas component in the disk, the situation is at present confusing. Absorption spectroscopy in the optical and UV shows a stable component at the same radial velocity as the star (Vidal-Madjar et al. 1986; Lagrange et al. 1998). One would expect radial expansion of this gas, caused by the radiation pressure of the star, and as a possible explanation a ring of atomic hydrogen has been proposed (Lagrange et al. 1998). If present, such a ring must be close to the star since widespread H I is not detected at 21 cm (Freudling et al. 1995). CO has been detected by means of UV spectroscopy (Roberge, Feldman, & Lagrange 2000), but sensitive searches for CO emission in the radio region have failed to detect this molecule (Liseau & Artymowicz 1998). Molecular hydrogen is not detected in UV absorption spectra (Lecavelier des Etangs et al. 2001), but, on the other hand, *Infrared Space Observatory*/Short-Wave Spectrometer spectroscopy (Thi et al. 2001) indicates $H_2$ emission lines that, if real (the signal-to-noise ratio is low), require large amounts of molecular hydrogen in a spatial distribution that has a void in the line of sight toward the star.

So far, it has not been possible to directly probe the velocity pattern along the disk, lacking the detection of spatially resolved gas emission (except a possible detection of Fe II emission very close to the star; Lecavelier des Etangs, Hobbs, & Vidal-Madjar 2000). In the present Letter, we report the detection of the resonance Na I doublet lines at 5990 and 5996 Å.

## 2. OBSERVATIONS AND RESULTS

The star $\beta$ Pic was observed in 2001 January 2–4 with the echelle spectrograph ESO Multi-Mode Instrument on the 3.5 m New Technology Telescope at ESO, La Silla, Chile. For the Na I D1/D2 observations, we used a 5′ long slit and therefore omitted the cross-disperser. Instead, we inserted an order-sorting interference filter, which was centered at 5890 Å and had a width of 60 Å. We have measured the filter profile and are in control of the leakage from the neighboring orders (less than 3% and 4%, respectively). With a wavelength resolution of $6 \times 10^4$ ($\Delta v = 5\ \mathrm{km\ s^{-1}}$), this instrumental setup can be viewed as some sort of a "spectroscopic coronagraph," in which the high dispersion is used to prevent the saturation of the detector (CCD) by the very bright stellar point source. Still, the overheads of the observing time were dominated by detector readout times since integration times of individual observations were typically only 300 s. The total integration time was chosen such that the co-added spectra should permit the detection of the faint light scattered off the disk by the dust, which was also achieved. Parallel with the disk (at position angle 30°.75; Kalas & Jewitt 1995), this time was 2.5 hr, whereas we spent a total of 36 minutes for observations with the slit oriented perpendicular to the disk. The seeing values determined from these observations are 1″.2, whereas the width of the slit was kept at 1″.0 in order to sample (on the CCD) the spectral resolution at the Nyquist frequency.

In addition to the two telluric emission lines, the parallel observations also show spatially extended Na I D emission, with both lines consistently redshifted to the heliocentric velocity of $\beta$ Pic (21 km s$^{-1}$). These observations are displayed

[1] Based on observations collected at the European Southern Observatory, Chile.

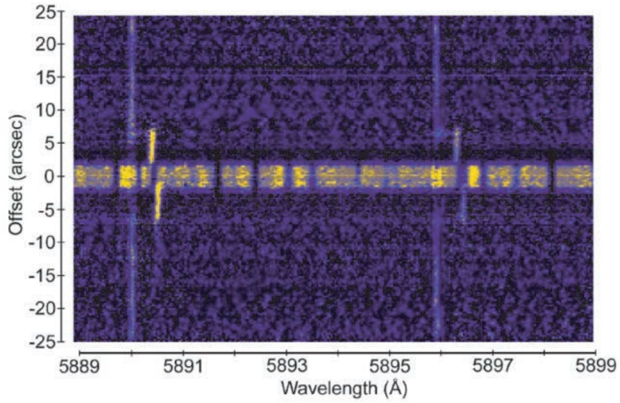


FIG. 1.—Spectral region around the Na I D lines toward $\beta$ Pic. The dispersion is along the horizontal axis, with wavelengths increasing to the right, and the scale is 0.035 Å pixel$^{-1}$ (1.8 km s$^{-1}$ pixel$^{-1}$). The spatial dimension is along the vertical axis, with the 1″ wide and 300″ long slit oriented along the position angle of 30°.75. The scale is 0″.27 pixel$^{-1}$ (5 AU pixel$^{-1}$), with positive values toward the southwest and the negative values toward the northeast. The (deliberately very much reduced) stellar continuum at the center of the figure is covered with telluric absorption lines, whereas the terrestrial ionospheric Na I D1/D2 emission lines extend over the entire vertical space. The Na I line emission from the $\beta$ Pic disk is seen redshifted with respect to the sky lines and with the intensity ratio 1 : 2. On either side of the star, the disk lines are either blue- or redshifted with respect to the systemic rest wavelength, represented by the disk gas absorption seen against the stellar continuum.

in Figure 1. In Figure 2, the distribution of the Na I emission along the slit, on either side of the stellar spectrum, is compared with the corresponding distribution of the dust. Evidently, both gas and dust show similar light distributions, suggestive of the coexistence of these species in the $\beta$ Pic disk.

## 3. DISCUSSION

### 3.1. *The Rotation of the Disk*

We first address the question of Keplerian rotation. Justified by the indications that there is no significant outward motion, we simply assume circular rotation. The distance to the star is 19.3 pc (Crifo et al. 1997). In order to interpret the velocity pattern, we must first find a radial density distribution of the Na gas component that results in the observed light distribution. For the moment, we ignore the difference between the two sides (Fig. 2) and use the average light distribution. Adopting a functional relation that is suitable for a broken power law,

$$n(\text{Na I}) \propto [(r/a)^{2b} + (r/a)^{2c}]^{-1/2},$$

where $n$(Na I) is the volume density of Na I at the radial distance $r$ (within the 1″ slit), we get a quite satisfactory fit to the observed projected light distribution with the following numerical values: $a = 89.5$ AU, $b = -1.28$, and $c = 3.44$. The distribution function is shown in Figure 3, and the fit to the observations in Figure 4.

Our observations are consistent with the circular Keplerian rotation of the gas (see Fig. 5), in which we have taken the measured seeing and spectral instrumental profile (using telluric absorption lines) into account. The best-fit mass, in a $\chi^2$ sense, equals $1.40 \pm 0.05\ M_\odot$. This model mass is less than that deduced from the stellar position in the H-R diagram, viz., $1.75\ M_\odot$ (e.g., Crifo et al. 1997). It is possible that this difference is due to radiation pressure (see § 3.3).

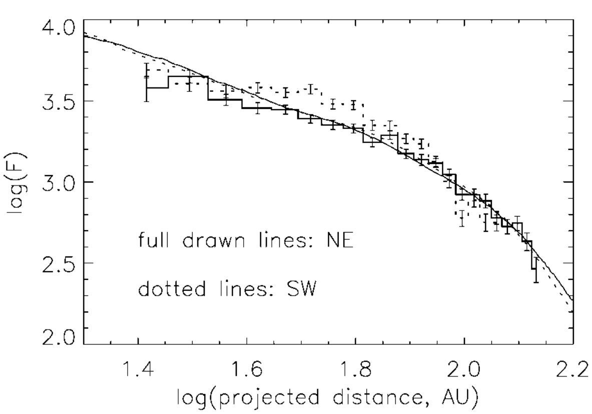


FIG. 2.—Radial distribution, for the two sides of the disk, of the Na I D2 line emission with error bars compared with that of the scattered stellar radiation caused by the dust (from Heap et al. 2000). The flux scale is arbitrary and adjusted to facilitate the comparison.

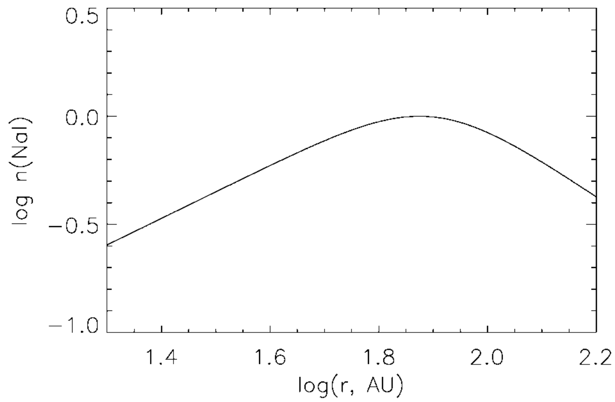


FIG. 3.—Derived radial distribution for Na I (normalized at the peak)

### 3.2. *The Light Budget*

The origin of the "stable gas" absorption has been extensively discussed, and there are arguments for a location very close to the star (Lagrange et al. 1998). If, on the other hand, the sodium emission far out in the disk is caused by the resonance scattering of stellar radiation, then, at least partly, the stable gas absorption must originate throughout the disk along the line of sight. We

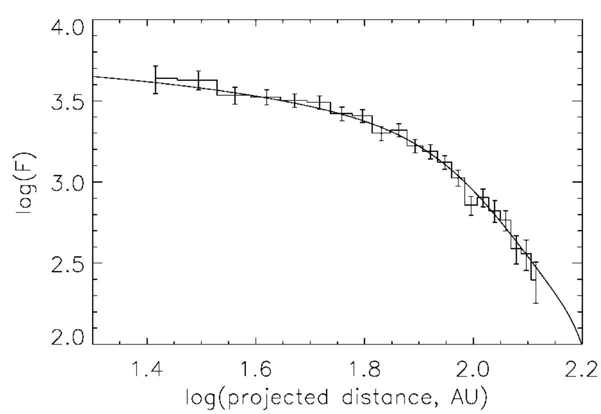


FIG. 4.—Projected radial distribution of the Na I D2 emission of the model (*solid line*) compared with that observed (the average of the southwest and northeast sides).

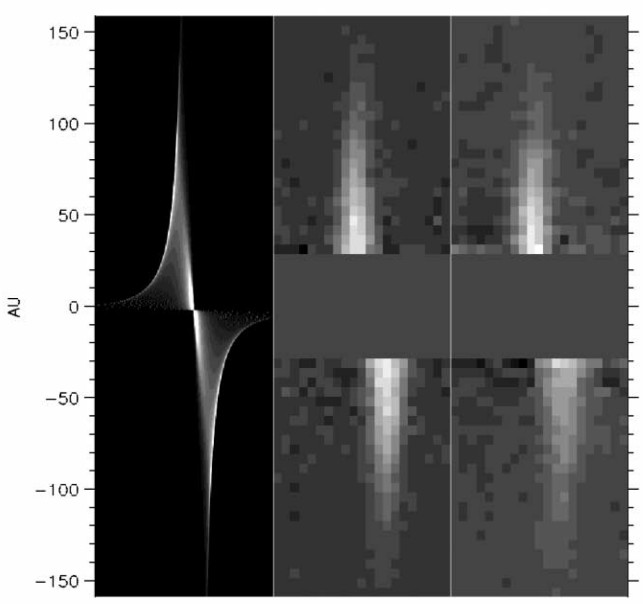


FIG. 5.—Comparison of the observed Na I D2 line with the results of theoretical model calculations. To the left, the model is displayed at spatial and spectral resolutions 10 times better than that observed. In the middle, we show the model degraded to the quality of the observations (including noise). As is seen, it compares well with the observations (to the right).

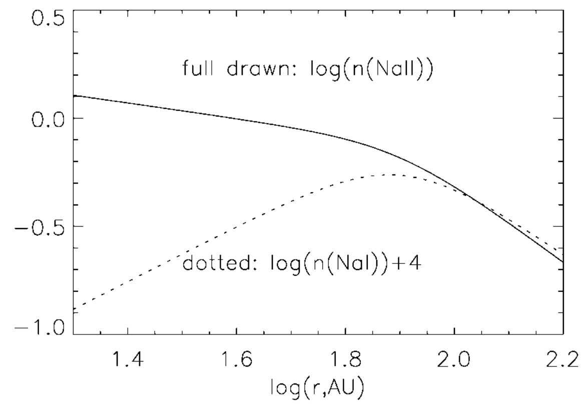


FIG. 6.—Derived number density (in units of $cm^{-3}$) for Na I and Na II. Only a small fraction ($<10^{-4}$) of the sodium is neutral.

measure an Na I D2 equivalent width in absorption of 9.4 mÅ, implying a column density of $N(\text{Na I}) = 7 \times 10^{10}$ $cm^{-2}$, in agreement with previous observations by Vidal-Madjar et al. (1986). In emission, a total equivalent width of 0.72 mÅ is obtained. This latter number is of course a lower limit since it does not include any line emission originating outside the 1″ wide slit of the spectrograph. It means that the disk, as seen from the star, must occupy at least a latitudinal angle of 8°.8. We start to detect the line emission at a distance of 30 AU, and at this distance the required thickness of the disk would be at least 4.6 AU. Since the slit width covers 19 AU, these estimates do not lead to any contradiction regarding the light budget under the assumption of resonance scattering. On the other hand, there is not much margin for the proposed dense H I ring (Lagrange et al. 1998) to contribute to the stable Na I absorption lines.

### 3.3. *The Radiation Pressure*

How, then, can we understand why the radiation pressure does not quickly accelerate the Na I outward in the same sense as it does, for instance, in comets (see Cremonese et al. 1997)? We first note that the momentum transfer caused by the resonance scattering vastly exceeds the gravity. Assuming a stellar mass of 1.75 $M_\odot$, we find that the force caused by the radiation pressure exceeds the gravitational force by a factor of 300. A possible explanation as to why we do not observe a radial velocity component is the presence of a relatively dense gas component. However, this would require very large amounts of gas far out in the disk. As an example, we consider the distance of 100 AU. Our observations exclude a radial velocity component exceeding 5 km $s^{-1}$, and assuming that the main gas component is atomic hydrogen, we find that the gas density must be at least $10^5$ $cm^{-3}$. Since the thickness (or scale height) of the gas component of the disk is unknown, it is hard to judge if this minimum density is in conflict with other observations.

Even though we cannot at present rule out this explanation for the balancing of the radiation pressure, we propose an alternative. Due to the low-ionization potential of Na I (5.1 eV), one would expect the stellar UV radiation to provide a high degree of ionization. Since Na II lacks strong transitions within the range of the stellar spectrum, the radiation pressure on the ionized sodium gas does not counterweigh the gravitation. Thus, if the gas density is low, a sodium atom will quickly take up speed outward. But it will stay neutral just for a short time, and then, as singly ionized, it will have a long time to adapt to the motion of the main gas component.

To quantitatively test this idea, we estimate the degree of ionization. Since we can exclude higher ionization stages (the ionization potential is 47 eV for Na II), the equation of ionization equilibrium reads

$$\frac{n(\text{Na II})}{n(\text{Na I})} = \frac{\omega(r)\Gamma_0}{\alpha_{\text{tot}}[T(r)]n_e(r)},$$

where $\omega$ is the dilution factor of the radiation density at the distance $r$ from the star compared with that at the stellar surface, $\Gamma_0$ is the ionization rate at the stellar surface, $\alpha_{\text{tot}}$ is the total recombination coefficient, and $n_e$ is the electron density. Using a model atmosphere from Allard, Hauschildt, & Schweitzer (2000) and cross sections from Cunto et al. (1993), we estimate that $\Gamma_0 = 205$ $s^{-1}$. Assuming 100 K as a typical electron temperature in the disk, we get $\alpha_{\text{tot}} = 3.85 \times 10^{-12}$ $cm^3$ $s^{-1}$ (Verner & Ferland 1996). The electron density remains to be estimated. The stellar far-UV continuum does not suffice to ionize H, He (if at all present), C, N, and O. Assuming solar abundances (Holweger & Rentzsch-Holm 1995) for elements with ionization potentials $\lesssim$8.3 eV (longward of 1500 Å), we estimate that $n_e \sim 50n(\text{Na II})$. If we finally assume a constant thickness of the disk (the half-power width of the dust disk is in fact close to constant from 30 AU and outward; see Heap et al. 2000), we can use the radial distribution derived for Na I in combination with the column density to derive the degree of ionization as a function of the distance to the star. We find that sodium is indeed highly ionized with $n(\text{Na I})/n(\text{Na}) < 10^{-4}$ throughout the disk. In Figure 6, we show the radial distribution of $n$(Na I) and $n$(Na II). These analytical results have been confirmed by self-consistent photoionization computations, which produce the observed line fluxes. The details will be given in a forthcoming paper.

We conclude that the radiation pressure on sodium, averaged over time, would be small. However, we must also estimate the speed that a neutral atom would typically achieve before it becomes ionized. Both the UV continuum and the sodium D lines are optically thin throughout the disk, and thus both the ionization rate and the resonance scattering rate roughly scale as the inverse square of the distance to the star. Therefore, the number of scattered photons per period of neutral state is constant, and we find that typically $1.5 \times 10^4$ scattering events will occur before an atom becomes ionized. The scattered radiation is essentially isotropic, and the transferred momentum would cause an outward velocity of merely 0.4 km $s^{-1}$. After that, there will be a long period of time during which the sodium ion will interact with the main gas components and conform to the general velocity pattern, whether it be basically circular Keplerian rotation or not. This also means that the radiation pressure may cause a slow, stepwise motion of each sodium atom outward, resulting in a net flow from the inner to the outer parts of the disk.

### 3.4. *The Amount of Atomic Gas in the Disk*

From the radial distribution of Na I, we were able to derive the radial distribution of Na II (Fig. 6). The number density is typically $n(\mathrm{Na}) = 1\ \mathrm{cm}^{-3}$, and the column density from 30 to 140 AU is $N(\mathrm{Na}) = 10^{15}\ \mathrm{cm}^{-2}$. If the Na/H ratio were solar, this would indicate a hydrogen column density of $N(\mathrm{H}) = 5 \times 10^{20}\ \mathrm{cm}^{-2}$. Further discussion of these aspects will be deferred to a forthcoming paper.

## 4. CONCLUSIONS

We have observed Na I D1 and D2 emission along the disk of $\beta$ Pic from a projected distance of 30–140 AU. The velocity pattern mimics circular Keplerian rotation, but the deduced mass is somewhat lower than that expected for an A5 V star (1.4 $M_\odot$ compared with 1.75 $M_\odot$). This difference is probably due to the radiation pressure that to some extent counterbalances the gravity. We find that the sodium gas is mainly ionized, with Na II/Na I around $10^4$, and for this reason, the radiation pressure does not accelerate the sodium gas component to high velocities. This is simply because the number of scattering events during a neutral period of a sodium atom would only suffice to give an outward velocity of 0.4 km $s^{-1}$, and then, during the typically $10^4$ times longer period of a singly ionized state, the radiation pressure is negligible. So there is plenty of time for the sodium gas to conform, through gas friction, to the motion of the main gas component (i.e., H, O, C, and N) that has only a weak direct interaction with the radiation field.

Finally, it is clear that the observations presented in the present Letter mark only a starting point of spectroscopic investigations since both the spectral and spatial resolutions as well as the stray-light level can be significantly improved on. In addition, other lines like the Ca II H and K doublet and a number of resonance lines in the UV, accessible from, e.g., the *HST*, will probably be detected in the disk.

## REFERENCES


Allard, F., Hauschildt, P. H., & Schweitzer, A. 2000, ApJ, 539, 366
Artymowicz, P. 1997, Annu. Rev. Earth. Planet. Sci., 25, 175
Augereau, J. C., Nelson, R. P., Lagrange A. M., Papaloizou, J. C. B., & Mouillet, D. 2001, A&A, 370, 447
Aumann, H. H. 1985, PASP, 97, 885
Cremonese, G., et al. 1997, ApJ, 490, L199
Crifo, F., Vidal-Madjar, A., Lallement, R., Ferlet, R., & Gerbaldi, M. 1997, A&A, 320, L29
Cunto, W., Mendoza, C., Ochsenbein, F., & Zeippen, C. J. 1993, A&A, 275, L5
Freudling, W., Lagrange, A.-M., Vidal-Madjar, A., Ferlet, R., & Forveille, T. 1995, A&A, 301, 231
Heap, S. R., Lindler, D. J., & Lanz, T. M. 2000, ApJ, 539, 435
Holweger, H., & Rentzsch-Holm, I. 1995, A&A, 303, 819
Kalas, P., & Jewitt, D. 1995, AJ, 110, 794
Lagrange, A.-M., Backman, D. E., & Artymowicz, P. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 639
Lagrange, A.-M., et al. 1998, A&A, 330, 1091
Lecavelier des Etangs, A., Hobbs, L. M., & Vidal-Madjar, A. 2000, A&A, 356, 691
Lecavelier des Etangs, A., et al. 2001, Nature, 412, 706
Liseau, R., & Artymowicz, P. 1998, A&A, 334, 935
Pantin, E., Lagage, P. O., & Artymowicz, P. 1997, A&A, 327, 1123
Roberge, A., Feldman, P. D., & Lagrange, A.-M. 2000, ApJ, 538, 904
Smith, B. A., & Terrile, R. J. 1984, Science, 226, 1421
Thi, W. F., et al. 2001, Nature, 409, 60
Verner, D. A., & Ferland, G. J. 1996, ApJS, 103, 467
Vidal-Madjar, A., Hobbs, L. M., Ferlet, R., Gry, C., & Albert, C. E. 1986, A&A, 167, 325
Vidal-Madjar, A., et al. 1994, A&A, 290, 245