

BROAD-BAND IMAGING OF THE BETA PICTORIS CIRCUMSTELLAR DISK¹

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ABSTRACT

The β Pictoris circumstellar disk is imaged at subarcsecond resolution between $5''$ and $15''$ from the star in the B , V , R and I_c bands. The shape of the emitted spectrum is indistinguishable within statistical uncertainty from that of β Pictoris itself. The surface brightness of the disk in the B , V , R and I_c bands at $6''$ from the star is 16.6, 16.3, 15.9 and 15.9 mag per square arcsecond, respectively. The results are consistent with the emission mechanism being scattering of starlight and the bulk of the scattering particles having sizes much greater than $1\ \mu\text{m}$.

Subject headings: stars: circumstellar shells — stars: individual (β Pic)

I. INTRODUCTION

A substantial far-IR excess first detected by the *IRAS* satellite (Aumann 1985*a, b*; Gillett 1986) closely followed by ground-based near-IR imagery (Smith and Terrile 1984) revealing a disklike highly flattened circumstellar nebula ~ 1000 AU in extent have made the nearby A5 V star β Pictoris the best candidate to date for a planetary or proto-planetary system beyond our own. Although reasonably coherent and self-consistent theories of formation and evolution of our solar system are available, it is still difficult to locate our system in a wider perspective. The discovery of even one other planetary system would obviously improve the situation dramatically. It is important, therefore, to confirm the planetary or protoplanetary nature of the β Pictoris disk and to investigate in greater detail its morphology and physical characteristics.

A direct measurement of the disk particle size distribution would represent a crucial step in this direction. A simple and effective diagnostic of the particles is the spectral signature of the disk emission in the optical especially if the emission mechanism is scattering of starlight. Consequently, we have undertaken to image the β Pictoris disk in the B , V , R , and I bands with $\sim 1''$ resolution. In this *Letter*, we report the results of these observations. They indicate that the shape of the emitted disk spectrum in the $4000\text{--}10000\ \text{\AA}$ range at this resolution cannot be distinguished within the observational uncertainty from the stellar continuum. Thus, the scattering must be essentially neutral or wavelength-independent as would be expected from a scattering medium where the bulk of the scatterers are particles of size much greater than $1\ \mu\text{m}$ in radius and the albedo is constant.

II. OBSERVATIONS AND DATA REDUCTION

The data described in this *Letter* were obtained on 1986 September 4–6 and November 27–28 at the 2.2 m MPI

¹Based on data collected at the European Southern Observatory, La Silla, Chile.

Cassegrain telescope at La Silla, Chile operated by ESO. The telescope focal plane was reimaged at $f/40$ by a coronagraph of our design onto an RCA backside-illuminated charge-coupled device (CCD) detector. The coronagraph consisted of a photographically etched occulting wedge situated at the telescope focal plane followed by an achromatic doublet and an appropriately designed apodizing mask to reduce diffracted stellar light from the telescope pupil. Before reaching the CCD, the radiation is filtered by a series of wide bandpass filters located on a commandable filter wheel. The CCD consists of 512×320 $30\ \mu\text{m}$ square pixels each corresponding to 5×10^{-3} arcsec² on the sky. The total rectangular field of view is, thus, $22''.5$ by $35''.9$. The projected width of the occulting finger on the detector was 60 pixels or $4''$. The instrumental design is discussed in more detail elsewhere (Burrows, Paresche, and Evzerov 1986).

The filters were selected to approximate as closely as possible the standard Johnson B, V, R, I sequence. The actual response achieved with our optical system expressed in CCD electrons per photon as a function of wavelength is shown in Figure 1 for the four bandpasses used in our investigation. The CCD conversion factor at our operating gain was taken to be 13.5 electrons per ADU. The results shown in this figure were obtained by convolving the measured efficiencies of each optical component with the spectrum of several bright stars, including β Pictoris, used as calibration sources observed unobscured by the occulting finger and with a neutral density (ND3) filter in the beam to avoid CCD saturation. The main source of calibration error is traceable to uncertainties in the stellar spectra and in the attenuation of this filter. We estimate an overall error of $\pm 20\%$ on the peak of the resulting bandpasses shown on Figure 1. The shape of the B , V , and R bands rather closely resembles the standard Johnson colors whereas the I band is more comparable to the Cousins I_c system (Bessell 1979).

Using the telescope TV autoguiding system, β Pictoris was placed behind the occulting wedge and precisely centered so that the spillover light distribution in a series of short acqui-

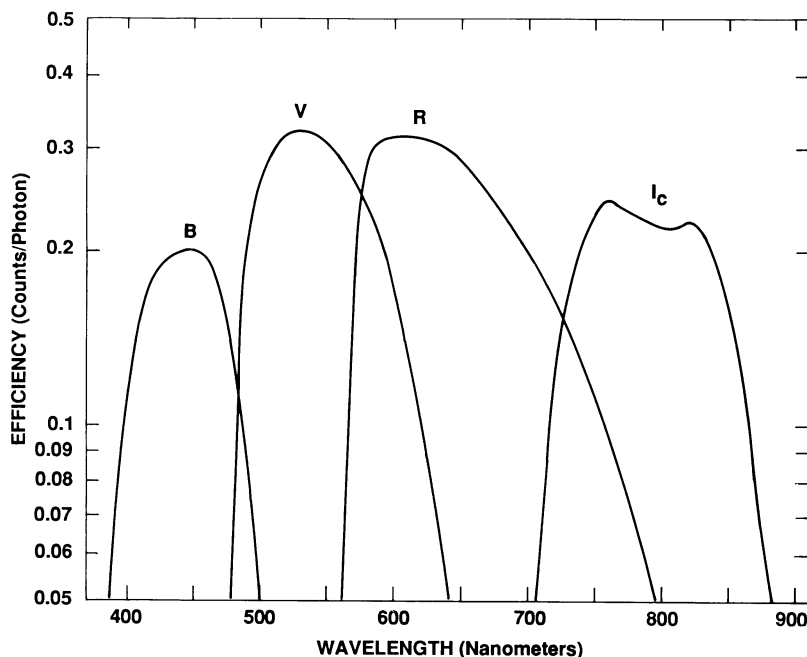


FIG. 1.—Overall efficiency of response of the optical and detector system as a function of wavelength for the four bands used

tion exposures with progressively less ND attenuation was as symmetrical as possible. Then, any ND filter remaining was removed and the exposure in the specified bandpass begun. At the end of the exposure on β Pictoris, the telescope was moved to the star δ Hydrus (A3 V, $V = 4.09$) or α Pictoris (A7 IV, $V = 3.27$) used as control and the procedure repeated. Focus and seeing conditions were monitored closely during the runs. Many of the observations were carried out with 0".8–0".9 seeing. Details of the data processing techniques used to extract the clean image of the disk are given elsewhere (Burrows *et al.*). Briefly, after masking, flat-fielding, and removal of cosmic-ray hits, a truncated least-squares fit between the β Pictoris and the control star image is made allowing the relative intensity, overall background, and spatial registration to vary. The best values for these parameters chosen in this way were then used to subtract the control star from the β Pictoris image.

III. RESULTS

An example of the results of such processing is shown in Figure 2 (Plate L2) which represents the difference image between β Pictoris and δ Hydrus in the I_c band and Figure 3 (Plate L3) which shows the difference image in the B band. Basically, all that remains in both cases is a bright feature inclined about 30° to the occulting wedge which, in the case shown in Figure 2, is oriented N–S with north pointing left and east pointing up. The width of the mask used in the data processing is 4".5, slightly larger than the occulting wedge at the position of the star. This was done to remove possible edge effects due to the wedge. The exposure times on β Pictoris were 30 minutes for the I_c and 2 minutes for the B band images.

The data displayed in Figure 2 confirm the existence of a highly flattened nebula or disk surrounding β Pictoris with a position angle in the sky of 30° extending out to at least $15''$ from the star. We can follow a monotonically rising intensity down to approximately $5''$ from the center of the star before the mask occults it. The disk is also clearly detectable in the B , V , R , and I_c bandpasses at comparable count rates. A total of 29 exposures on β Pictoris in these passbands were carried out in the course of the two 1986 observing runs. The disk appears clearly in all and, most significantly, is just as evident when the CCD and coronagraph axes are rotated 90° so that the occulting mask runs E–W rather than N–S, and the disk image appears rotated 90° .

The FWHM of the disk is found to be about $2''$ – $3''$ for separations of $6''$ – $12''$ from the central star as found by Smith and Terrile (1984) and is independent of color. This value is of order 3 times the diameter of the seeing disk. We conclude that the nebula is resolved and exhibits a finite thickness of about 50 AU assuming a distance of 16.7 pc. This could be the actual thickness of the disk seen precisely edge-on, or may represent the effect of a slight tilt of magnitude 5° – 10° of the plane of a thin disk with respect to the line of sight.

IV. ANALYSIS

The color of any point on the disk can be easily compared to that of β Pictoris itself by computing the dimensionless ratio $Q_i(r) = [N_i^d(r)/N_I^d(r)]/[N_i^*/N_I^*]$ for points at the center of the light distribution of the observable disk in the B , V , and R images at varying distances r in arcseconds from the central source with all count rates normalized to those in the I_c band. In the expression for Q_i , N_i^d and N_I^d represent the count rates from the disk in the i and I bands, respec-

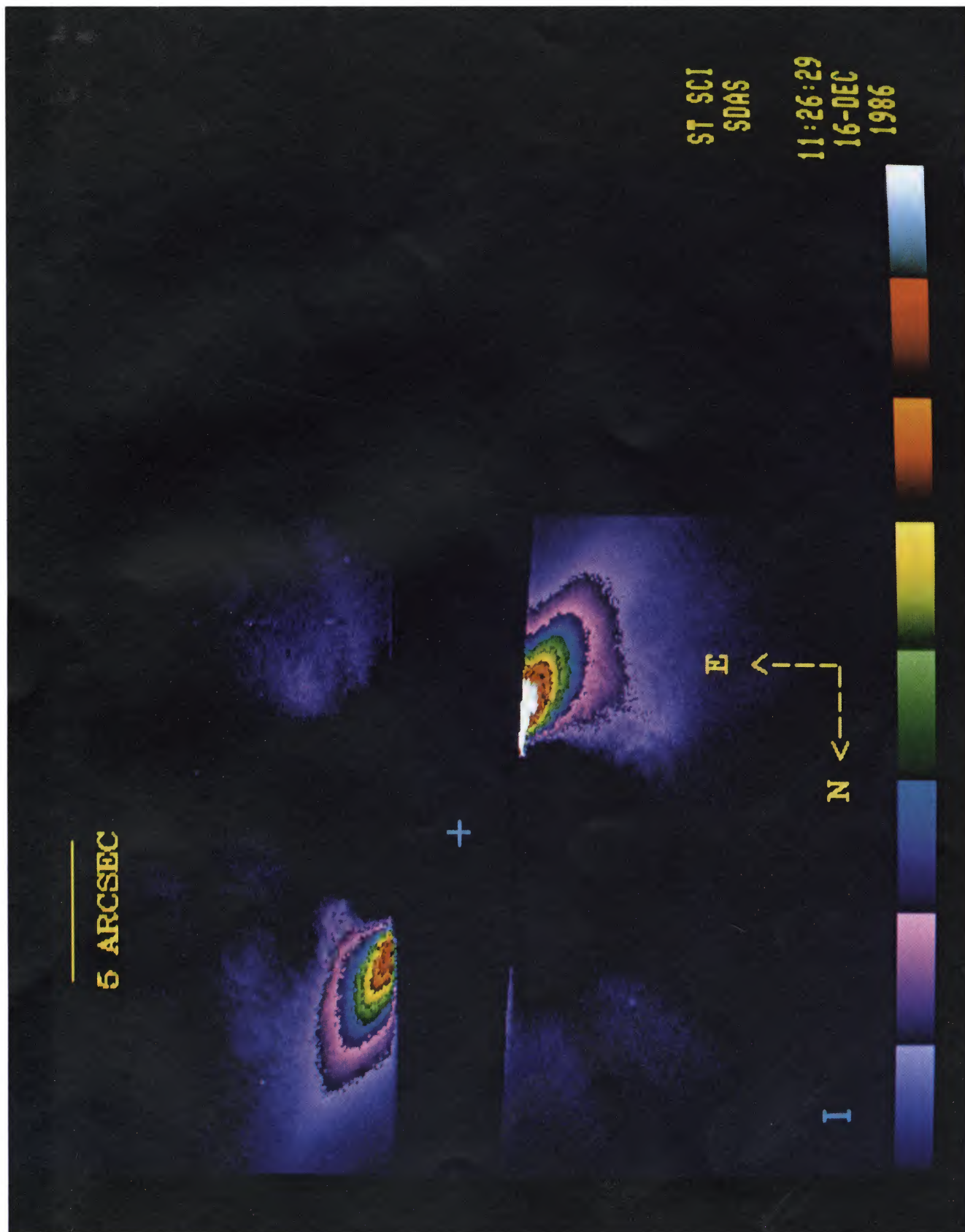


FIG. 2.—False color image of the β Pictoris circumstellar disk taken in the I_c band centered at 7900 Å. The observed intensity is color coded as shown on the bar at the bottom of the picture where each step equals 250 counts from a maximum of 1500 counts per pixel for a 30 minute integration.

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PLATE L3

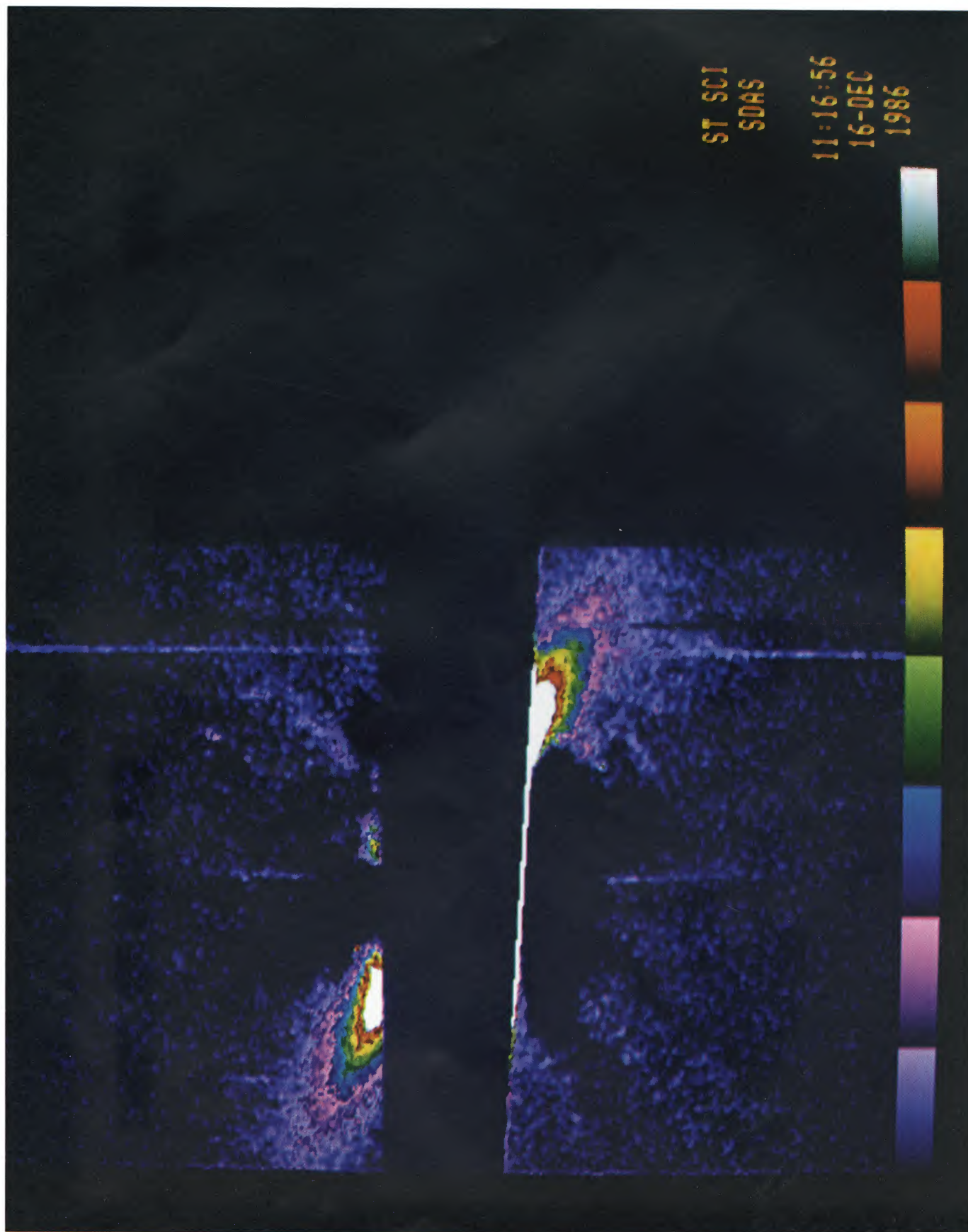


FIG. 3.—Same as Fig. 2 for the B band centered at $4400 \text{ \AA}$
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TABLE 1
COLOR RATIOS

r	Q_B	Q_V	Q_R	N_I^d (counts per pixel per 30 minutes)
6''	0.87 ± 0.25	0.94 ± 0.13	1.28 ± 0.15	1350 ± 100
7''	0.77 ± 0.15	1.05 ± 0.17	1.26 ± 0.16	915 ± 75
8''	0.84 ± 0.25	1.00 ± 0.21	1.20 ± 0.19	590 ± 50
9''	0.92 ± 0.25	0.97 ± 0.18	1.17 ± 0.15	365 ± 30
10''	0.83 ± 0.3	1.01 ± 0.23	1.18 ± 0.23	245 ± 30
11''	0.83 ± 0.3	0.99 ± 0.27	1.19 ± 0.4	170 ± 25
12''	0.84 ± 0.5	1.16 ± 0.4	1.20 ± 0.38	120 ± 20
Mean	0.84 ± 0.28^a	1.01 ± 0.22^a	1.21 ± 0.24^a	...

^a The error given here is the mean error, as the errors are dominated by systematic effects.

tively, while N_i^* and N_r^* represent the corresponding count rates from the unobstructed β Pictoris. If $Q_i = 1$, the disk has the same color as the star and the scattering coefficient is independent of wavelength while if Q_i is larger or less than 1, the disk is bluer or redder than the star, respectively.

Using the measured count rates from the center of the NE extension of the disk and from the star in the B , V , R , and I bands to compute Q_i , we find the values listed in Table 1 for the various bandpasses and points on the disk together with their errors. Also listed in this table are the corresponding values of N_I^d in counts per pixel in a 30 minute exposure. At 6'' from the star, the tabulated value of this parameter corresponds to a disk surface brightness of 15.9 I_c magnitudes per square arcsecond, in reasonable accord with the measurements of Smith and Terrile (1984) in the Johnson I band centered at 8900 Å. The corresponding surface brightness in the B , V , and R bands are 16.6, 16.3 and 15.9 mag per square arcsec, respectively.

The uncertainties in the computed Q_i stem mainly from uncertainties in the best-fit parameters used in the subtraction process, in slight registration errors, seeing changes between images and in possible color effects in the ND3 filter used to attenuate the unobscured star. The associated errors of the measurements were computed by repeating the calculations with all the available images in various combinations and with differing assumptions as to the best fit parameters, and by correcting for a small decrease in transmission of the ND3

filter in the I_c band. To a high degree of confidence, therefore, all the values shown in Table 1 can be considered to be consistent with $Q = 1$ for the observed range of distances and colors. The light distribution in all four bands is remarkably symmetrical with respect to the center of the star for all the separations listed in Table 1. Consequently, the results tabulated therein are equally applicable to both the NE and SW extensions of the disk.

This result confirms the hypothesis that the radiation observed emanating from the disk is due to scattering of β Pictoris starlight. It also confirms that the bulk of the scattering particles are much larger than the wavelength of the radiation sampled during our investigation. This conclusion is independent of any assumption as to the origin of the far-IR excess seen by *IRAS*, i.e., the scattering particles need not necessarily be those responsible for the bulk of the far-IR emission.

The observations are clearly consistent with scattering by large particles with a constant reflectivity. They are clearly inconsistent with the scattering being proportional to the inverse fourth power of the wavelength which would be characteristic of gas or small particle Rayleigh scattering. Indeed the mean values of Q are all consistent with unity, within our stated errors. There is no indication of a trend to larger scattering at shorter wavelengths. Thus there is no evidence for gas or very small particles at the present level of accuracy. For example, if only 5% of the brightness in the I band were due to Rayleigh scattering, and the rest were due to wavelength independent scattering, Q would be about 1.45 in the B band. This is inconsistent with the observations.

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REFERENCES

Aumann, H. H. 1985a in *IAU Symposium 112, The Search for Extraterrestrial Life: Recent Developments*, ed. M. D. Papagiannis (Dordrecht: Reidel), p. 43.

_____. 1985b, *Pub. A.S.P.*, **97**, 885.

Bessell, M. S. 1979, *Pub. A.S.P.*, **91**, 589.

Burrows, C., Paresce, F., and Evzerov, A. 1986, *Bull. AAS*, **18**, 1027.

Gillett, F. C. 1986, in *Light on Dark Matter*, ed. F. P. Israel (Dordrecht: Reidel), p. 61.

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

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