DISTRIBUTION OF DUST IN THE DISK AROUND BETA PICTORIS

Takenori Nakano
Nobeyama Radio Observatory, National Astronomical Observatory
Nobeyama, Minamisaku, Nagano 384-13, Japan

1. Introduction

Large far-infrared excesses in some nearby main-sequence stars, revealed by the *Infrared Astronomical Satellite* (*IRAS*), have been interpreted as being due to thermal radiation from dust orbiting the stars, heated to about 100 K by the stellar radiation (Aumann *et al.* 1984; Aumann 1985; Sadakane and Nishida 1986). The existence of solid circumstellar material is commonly interpreted in the context of planet formation, and the dust has been suggested to be formed by collisions of planetesimals (Nakano 1987, 1988).

The excesses in β Pic are outstanding among these stars. Using a CCD camera supplied with a coronagraph, Smith and Terrile (1984) obtained at the I band centered at wavelength $\lambda \approx 0.89\mu$m a high resolution image of a thin disk around β Pic which is seen nearly edge-on, and found that the surface brightness along the central line of the image can be approximated by a power law

$$I(\epsilon) \propto \epsilon^{-\mu} \tag{1}$$

with $\mu \approx 4.3$ for separation angle ϵ from the star between $6''$ and $25''$, or separation distance between 100 and 400 AU. Paresce and Burrows (1987) obtained CCD images of the β Pic disk at the B, V, R, and I_c bands. The surface brightness at the I_c band centered at 0.79μm is approximated by equation (1) with $\mu \approx 3.6$ between 100 and 200 AU (Artymowicz, Burrows, and Paresce 1989).

There has been some controversy on the density distribution of dust, $n(r)$, at distance r from the star. Assuming that dust is a nearly isotropic scatterer and has the same size distribution everywhere and that the disk has a finite radius of 500AU, Smith and Terrile (1984) found that the observed surface brightness distribution can be reproduced if $n(r) \propto r^{-3}$. Using the inversion equation Buitrago and Mediavilla (1986) reached a conclusion that although a slowly changing distribution like $n \propto r^{-1}$ is acceptable, the distributions steeper than $n \propto r^{-1.5}$ should be rejected because these distributions can be consistent with the observed surface brightness distribution only with a physically unacceptable scattering function. If dust is replenished at a constant rate from sources which are distributed only outside a circle of radius, say r_s, and dust is in equilibrium under the Poynting-Robertson drag, we have $n \propto r^{-1}$ at $r < r_s$ (Leinert, Röser, and Buitrago 1983). This fact was sometimes regarded as a support to Buitrago and Mediavilla's result (*e.g.*, Backman and Gillett 1987).

A.C. Levasseur-Regourd and H. Hasegawa (eds.), Origin and Evolution of Interplanetary Dust, 421–424.

Recently I investigated the dust density distribution using the inversion equation (Nakano 1990). This is a short report of this investigation with some addition.

2. The Intensity of the Scattered Light

A distant observer seeing a dust disk edge-on receives the scattered light of intensity

$$I(\epsilon) = \int n(r)\sigma(r,\theta)F_0\left(\frac{r_0}{r}\right)^2 dx, \tag{2}$$

where $\sigma(r,\theta)$ is the differential scattering cross section of a dust particle at scattering angle θ, r_0 is the outer radius of the disk, F_0 is the stellar radiation flux at $r = r_0$, and x is the distance from the observer along the line of sight. We have assumed that the disk is transparent to both stellar and scattered radiation as is the case for the β Pic disk at least at $r \gtrsim 100$ AU (Smith and Terrile 1984). When dust has some size distribution, $n(r)\sigma(r,\theta)$ should be regarded as the sum over the size distribution. Using relations $r/\sin\epsilon = x/\sin(\theta-\epsilon) = D/\sin\theta$, D being the distance from the observer to the star, we can rewrite equation (2) as

$$I(\epsilon) = \frac{F_0 r_0^2}{D\sin\epsilon}\int_{\theta_0(\epsilon)}^{\pi-\theta_0(\epsilon)} n(r)\sigma(r,\theta)d\theta, \tag{3}$$

where $\theta_0(\epsilon) \equiv \arcsin[(D/r_0)\sin\epsilon]$ is the scattering angle at the near end of the disk along the line of sight.

We assume that the θ-dependence of $\sigma(r,\theta)$ is the same everywhere and adopt a power-law distribution

$$n(r)\sigma(r,\theta) = n_0\sigma_0\left(\frac{r}{r_0}\right)^{-\nu} f(\theta), \tag{4}$$

where n_0 and σ_0 are the number density of dust particles and the total scattering cross section of a dust particle, respectively, at the outer boundary $r = r_0$. From equations (3) and (4) we have

$$I(\epsilon) = \frac{F_0 n_0\sigma_0 r_0^{\nu+2}}{D^{\nu+1}\sin^{\nu+1}\epsilon}\int_{\theta_0(\epsilon)}^{\pi-\theta_0(\epsilon)} f(\theta)\sin^\nu\theta d\theta. \tag{5}$$

Although the β Pic disk has been imaged only inside 400 AU, it must have somewhat larger extent. We shall consider the following two cases on the distribution of the integrand $f(\theta)\sin^\nu\theta$.

a) The case where most of the scattered light comes from the part of the line of sight nearest to the star.

In this case we can take r_0 sufficiently large and then $\theta_0(\epsilon) \approx 0$, and we have from equation (5)

$$I(\epsilon) \propto \epsilon^{-(\nu+1)}, \tag{6}$$

because $\epsilon \ll 1$. Thus the ϵ-dependence of the surface brightness is solely determined by the distribution of particles, and the observed surface brightness of the β Pic disk can be reproduced with $\nu \approx 2.6 - 3.3$ in agreement with Smith and Terrile (1984).

https://doi.org/10.1017/S0252921100067221 Published online by Cambridge University Press

b) The case where most of the scattered light comes from the outer part of the line of sight.

Differentiation of equation (5) with ϵ and some manipulation lead to the so-called inversion equation (Buitrago and Mediavilla 1986)

$$f(\theta_0) + f(\pi - \theta_0) = -\frac{I(\epsilon)\cos\theta_0}{F_0 n_0 \sigma_0 r_0}\left(\nu + 1 + \frac{d\log I}{d\log\epsilon}\right). \tag{7}$$

If the scattered light comes mostly from the outer part of the disk because of the steep forward scattering by dust and/or slowly changing density distribution, $F_0 n_0 \sigma_0 r_0 f(\theta_0)$ must be greater than $I(\epsilon)$. In this situation the quantity in parentheses in equation (7) must be at least of the order of unity. For $\nu \approx 1$ and the observed $I(\epsilon)$, it is definitely non-zero and is almost independent of ϵ. Hence from equation (7) the ϵ-dependence of the surface brightness must be determined by the scattering function $f(\theta)$ independent of the density distribution. For the observed surface brightness given by equation (1) with $\mu \approx 3.6 - 4.3$, the particles must be markedly forward-scattering. The backward scattering may not be so conspicuous as the forward scattering as inferred form the scattering function of the interplanetary dust which is responsible for the zodiacal light (Leinert *et al.* 1976). Therefore equations (1) and (7) require that the scattering function must satisfy

$$f(\theta) \propto (\sin\theta)^{-\mu}\cos\theta \tag{8}$$

at small θ. The scattering function for the interplanetary dust (Leinert *et al.* 1976) is pretty well reproduced by equation (8) with $\mu \approx 2$ at $2.5° \lesssim \theta \lesssim 30°$. The scattering function given by equation (8) with the observed values $\mu \approx 3.6 - 4.3$ is quite different from that for the interplanetary dust. Thus if the β Pic disk has a slowly changing density distribution with $\nu \lesssim -(d\log I/d\log\epsilon) - 2 = \mu - 2$, which makes the quantity in parentheses of equation (7) definitely negative, the particles must have the special scattering property given by equation (8), and they must be much more steeply forward-scattering than the interplanetary dust.

3. Discussion

The inversion equation (7) must be satisfied even for case (a) where the scattered light comes mainly from the part of the line of sight nearest to the star. In this case we have $I(\epsilon) \gg F_0 n_0 \sigma_0 r_0 f(\theta_0)$. Hence the left-hand side of equation (7) is a minor term and the two terms in parentheses, $\nu + 1$ and $d\log I/d\log\epsilon$, must nearly cancel each other, or $\nu + 1 + d\log I/d\log\epsilon \approx 0$. From this we again obtain equation (6).

Buitrago and Mediavilla (1986) considered that the density distribution with $\nu \approx 3$ was unacceptable because equation (7) with the observationally determined $d\log I/d\log\epsilon$ gives a physically unreasonable scattering function, *e.g.*, $f(\theta)$ taking a negative value at some ranges of θ.

However, the observed surface brightness must include some uncertainty. The derivative $d\log I/d\log\epsilon$ calculated from the observed $I(\epsilon)$ may have even larger uncertainty. Thus the quantity in parentheses of equation (7) with $\nu \approx \mu - 1$ must fluctuate around zero. A model fitting with a single power-law distribution given by equation (4) may also give rise to a fluctuation around zero. For instance, if the actual distribution of $n\sigma$ has an index ν slightly larger in the outer region than in the inner region, $|d\log I/d\log\epsilon|$ must be somewhat larger in the outer region than in the inner region. If we approximate such a distribution of $n\sigma$ with a single power law, the right-hand side of equation (7) would be negative in the inner region and positive in the outer region. Thus the behavior of the scattering function obtained from equation (7) cannot be used as a check of simplified models when the terms in the parentheses nearly cancel each other. A small fluctuation in $d\log I/d\log\epsilon$ should be attributed to the deviation of $n\sigma$ from a simple power law as well as to uncertainties in the observations.

If we approximate the scattering function as $f(\theta) \propto \theta^{-\lambda}$ at some range of small θ, the contribution of the outer region to the scattered light is small when $\nu > \lambda - 1$ as seen from equation (5). Thus the assumption in case (a) in §II is consistent with the result for, *e.g.*, $\lambda \approx 2$, a value suggested from the observations of the zodiacal light.

For case (a) in §II we have obtained $\nu \approx \mu - 1$ by assuming that the disk has a size much larger than the observed size. If the size is not so large, ν must deviate somewhat from $\mu - 1$. In reality Smith and Terrile (1984) obtained $\nu \approx 3.1$ instead of 3.3 for $\mu \approx 4.3$ by taking $r_0 \approx 500$AU, only 25 % larger than the radius of the region observed by them.

So far we have assumed that the apparent thickness of the β Pic disk is nearly equal to the real thickness and the line of sight can be taken nearly on the midplane of the disk. If the apparent thickness is due mainly to tilting of the disk to the observer and the real thickness is much smaller, we can find immediately that the surface brightness is given by equation (6). Thus the index to $n\sigma$ must again be $\nu \approx 2.6 — 3.3$.

The distribution $n \propto r^{-1}$ has found some acceptance because this distribution is realized when dust sources are distributed only outside the observed region and dust is in equilibrium under the Poynting-Robertson drag as mentioned in §1. However, the dust distribution can be steeper than r^{-1} when dust sources are distributed in the observed region, and can be consistent with $n\sigma \propto r^{-(\mu-1)}$.

I would like to thank Dr. T. Mukai for valuable discussion. This work was supported partly by the Grants-in-Aid for General Scientific Research (63540193) and for Scientific Research on Priority Areas (Origin of the Solar System 01611006) of the Ministry of Education, Science, and Culture, Japan.

References

Artymowicz, P., Burrows, C., and Paresce, F., 1989, *Astrophys. J.*, **337**, 494.
Aumann, H. H. 1985, *Publ. Astr. Soc. Pacific*, **97**, 885.
Aumann, H. H., *et al.* 1984. *Astrophys. J. (Letters)*, **278**, L23.
Backman, D. E., and Gillett, F. C. 1987, *Cool Stars, Stellar Systems, and the Sun*, ed. J. L. Linsky and R. E. Stencel (Berlin: Springer), p. 340.
Buitrago, J., and Mediavilla, E. 1986. *Astr. Astrophys.*, **162**, 95.
Leinert, C., Link, H., Pitz, E., and Giese, R. H. 1976, *Astr. Astrophys.*, **47**, 221.
Leinert, C., Röser, S., and Buitrago, J. 1983, *Astr. Astrophys.*, **118**, 345.
Nakano, T. 1987, in *IAU Symposium 115, Star Forming Regions*, ed. M. Peimbert and J. Jugaku (Dordrecht: Reidel), p. 301.
Nakano, T. 1988, *Mon. Not. Roy. Astr. Soc.*, **230**, 551.
Nakano, T. 1990, *Astrophys. J. (Letters)*, **355**, L43.
Paresce, F., and Burrows, C. 1987, *Astrophys. J. (Letters)*, **319**, L23.
Sadakane, K., and Nishida, M. 1986, *Publ. Astr. Soc. Pacific*, **98**, 685.
Smith, B. A., and Terrile, R. J. 1984, *Science*, **226**, 1421.

https://doi.org/10.1017/S0252921100067221 Published online by Cambridge University Press