Polarimetric confirmation of the dust disk around BD+31°643

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The tentative detection of a dust disk around the main sequence star BD+31°643 was recently announced by Kalas & Jewitt[1], representing only the second such known object. Due to its location within a patchy reflection nebulosity (IC348), supporting observations are of crucial importance to confirm this identification. Here, we present multi-band visual polarimetry which supports their discovery. We show that the geometry of the polarization can be understood in terms of multiple scattering within an optically thick disk, yielding the observed polarization parallel to the long axis of the observed edge-on disk. The wavelength dependence of the polarization (magnitude & direction) can be well fitted by a linear combination of light scattered by the dust disk and Rayleigh scattering from the polar regions of the disk. We find that the poles of the disk are oriented parallel to the polarization of the majority of background sources in the field and hence probably of the magnetic field in the cloud, as would be expected from star formation theory.

Starlight can be polarized due to several mechanisms; (1) intrinsically through magnetic phenomena in the stellar photosphere[2], (2) by Rayleigh or Thompson scattering in reflection nebulae, (3) by single or multiple scattering in circumstellar material[3] or (4) by passage through foreground interstellar material, threaded by a magnetic field[4]. The latter two mechanisms imply distinct geometrical signatures and, in the case of interstellar polarization, a clear wavelength dependence. Interstellar polarization is general] y agreed to result from the alignment of prolate dust grains spinning with their minor axis parallel to the magnetic field, hence giving rise to selective extinction, causing polarization parallel to the projected magnetic field direction. The polarization from circumstellar material differs in its implied direction depending on whether the photons undergo single or multiple scattering. The latter case would imply polarization parallel to the long axis of the disk projection seen on the sky[3]. For interstellar polarization, the wavelength dependence in the optical part of the spectrum has been found to generally show a broad peak around 6000Å, falling off to both the red and the blue. This dependence can be parametrized by the empirical Serkowski-Wilking[5] relation:

$$p(a) = p_{max} \exp\{-K " \ln^2(\lambda/\lambda_{max})\} \quad (1)$$

where p is the polarization, K is a parameter control I i ng the width of the peak and p_{max} and λ_{max} are the polarization and wavelength at the location of the peak, respectively. Although this is a strictly empirical formula, some theoretical justification comes from Mie scattering theory[6]. For circumstellar polarization no general wavelength dependence has been found[7] although some sources are well fitted by equation (]). It is, however, important to remember for circumstellar disk sources that the population observed so far are pre-main-sequence sources and hence possibly somewhat distinct from the object discussed herein.

As part of a larger study of the magnetic field structure in the Perseus molecular cloud complex[8], we observed BD+3 10643 in 1994, October 2-5, using the photopolarimeter[9] on the 82" (2.1 m) telescope at McDonald Observatory in the Extended Johnson System (UBVRI). The polarized standard HD 154445 was used to fix the instrument direction relative to the sky, assuming θ_{ref}=90. 10 for all bands except the U band for which we assumed θ_{ref}=87.9°[10]. The instrumental polarization was determined from the unpolarized standard HD 154345 and was found to be invariant throughout the observations. A standard reduction procedure was employed to remove instrumental polarization by correcting the Stokes parameters. All stars observed were selected to have known spectral classification and hence known distances. For those sources where independent observations exist[11,12], the results agree to within reported measurement uncertainties. Most of the observed stars were background sources, with the exception of a few stars in IC348, including BD+3 10643. For the background stars we expect only to detect interstellar polarization due to the Perseus cloud (distance≈260pc[13]) since they arc predominantly early type field stars not expected to have circumstellar material. We have also made use of polarization measurements by Goodman c: al[14], Il'in et al [11], and Joshi et al [15], but have selected only those stars for which reliable spectral classifications exist. In table 1 we list the results for stars near BD+31°643 plot the polarization vectors overlaid on a map of the CO (J= 1 -O) emission[16] in figure 1. As can be seen the polarization of the background stars indicates a magnetic field running NW-SE while the polarization of BD+3 10643 is SW-NE. Dots the polarization of these background sources trace the magnetic field in the Perseus cloud or just in the ambient, possibly foreground gas? The polarization structure in Perseus is complex[14] with what looks like a bifurcated distribution one polarization component being parallel to the cloud and one toward sources in the densest parts of the cloud being perpendicular to the cloud. The stars responsible for the latter determinations have somewhat uncertain distances, since they have not been spectroscopically classified and may in fact be young embedded stars. One interpretation of the polarization behaviour is made more intriguing by the detection of the disk around BD+3 10643, namely that the polarization of latter sources result from scattering by circumstellar material.

From the theory of star formation in a magnetized molecular cloud, we would expect the poles of a circumstellar disk to be parallel to the magnetic field direction [17]. As can be seen from figure l of Kalas & Jewitt, the major axis of the optically detected disk of BD+3 10643 is approximately perpendicularly to the long axis of the cloud and hence is perpendicular to the local magnetic field, traced by the background stars. Wc hence **suggest that the sources with polarization angles around -50° in the region around B1[14] are good candidates for further searches for circumstellar disks.**

The polarization of BD+3 10643, can be understood in the context of the theory of polarization from optically thick circumstellar disks[3]. As shown by Ménard & Bastien, an optically thick disk seen edge-on will result in polarization parallel to the projection of the disk, due to multiple scattering in the disk. In contrast, a singly scattered photon will tend to be polarized perpendicularly to the line connecting the star and the scattering grain. Based on available photometry, the extinction towards BD+3 10643 is about A_V=2.7mag.[12] which would support the conclusion that we're seeing multiply scattered light from BD+31°643. As a comparison, the polarization of the surrounding of the only other known disk around a main-sequence star; β Pictoris, shows that for β Pic the polarization is perpendicular to the disk and dominated by the reflection nebulosity surrounding the star[18]. This difference is however not surprising since the extinction towards β Pic is only $A_V \approx 0.2$ msg. Hence, in one case (β Pic)wc are seeing the star nearly directly while in the other case it is heavily obscured.

Upon inspection of the wavelength dependence of the polarization for the stars *in* the vicinity of BD+3 10643 it was immediately clear that, while the background stars show polarization in general agreement with the Serkowski-Wilking relation, BD+3 10643 itself was not well fitted by this functional form. Further, while the angle of polarization stays constant as a function of wavelength for the background sources, that for BD+3 10643 shows a strong deviation for the two bluest filters. In figure 2 we have plotted the measured values of the normalized Q & U Stoke's parameters in the five filters for BD+31 "643. Because our measurements are acquired with a large-aperture diaphragm photometer we cannot distinguish between different parts of the circumstellar environmen t.

Given that the star is on the main sequence and shows no sign of a circumstellar envelope (besides the disk), the most likely mechanism for the blue polarization excess would seem to be Rayleigh scattering from low density material in the polar regions of the disk. Since the polarization does not lend itself to a linear combination of terms, we used the Q & U measurements to fit the data to two models. We used a Marquat-Levenberg χ^2 minimization technique[19] and fitted the Serkowski-Wilking relation by itself, and also a linear combination of the Serkowski-Wilking relation and a Rayleigh scattering term. In the latter case we allowed the two polarization terms to have independent polarization angles, hence[20];

$$Q = p_{max}\exp\{-K\cdot\ln^2(\lambda/\lambda_{max})\}\cdot\cos(2\theta_S) + \text{cl-'.}\ \cos(2\theta_R)$$
$$U = p_{max}\exp\{-K\cdot\ln^2(\lambda/\lambda_{max})\}\cdot\sin(2\theta_S) + c\lambda^{-4}\cdot\sin(2\theta_R) \qquad (2)$$

where c is a normalization parameter for the Rayleigh term, θ_S and θ_R are the angles of polarization (E of N) for the Serkowski-Wilking and Rayleigh terms respectively, and the other parameters are defined as above. We feel the usc of the Serkowski-Wilking relation is justifiable since 1) it approximates the results of Mie scattering and 2) the polarization magnitude and direction for the three reddest filters would by themselves yield an acceptable fit to this functional form. In figure 2 we have ova-plotted the best fits to the data for these two functions. Although the Q measurements are equally well fitted by either functional form, the U measurements arc clearly better fitted by the combined form. A formal comparison of the fitting errors through the use of the F-distribution[21] yields that the two extra fitting parameters are warranted at the 95% confidence level. In table 2 we list the best fit parameters. As can be seen the polarization angle of the S-W part is close to that of the disk as measured from the optical images (≈-40°) , while that of the Rayleigh term is about 20° offset. Since the detailed geometry of the dust disk, polar region and viewing angles are unknown, these results seem quite reasonable. Therefore, in summary, three independent observational facts based on our polarimetry support Kalas & Jewitt's identification of a dust disk around BD+3 10643; The disk (as seen in optical images) is oriented perpendicular to the ambient magnetic field, the polarization of the star is parallel to the major axis of the projected disk and the wavelength dependence of the polarization is well fit by a combination of polarization from the disk and light Rayleigh scattered by material at the poles of the disk.

Acknowledgments

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TABLE 1

Star	R.A. (1950)	Dec. (1 950)	θ [°] (EofN)	p [%]	V[mag.]	A_v	Sp. Class.	r [pc]
HD 22951	3:39:12.0	33:48:22	78	0.8	5.0	0.9	B0.5V	342
HD 278934	3:40:04.0	33:25:48	43	1.4	10.8	1.8	A1V^p	287
G72	3:40:17.0	32:08:39	154	2.7	12.8	1.7	K0III^p	1159
IC 3484	3:41:00.2	31:57:51	23	2.6	9.9	1.2	A3V^p	238
IC 348#20	**3:41:25.8**	**32:00:22**	**145**	**1.4**	**8.5**	**2.7**	**B5V**	252
HD 281167	3:41:56.0	30:44:36	**106**	**3.0**	**9.9**	1.8	A0IV^p	380
G75	3:42:01.0	32:25:29	**140**	**2.3**	**13.3**	3.0	K3III	899
G77	3:42:15.0	32:29:41	**79**	**3.2**	**11.7**	**3.1**	A7m^p	245
G79	3:42:49.0	32:03:49	**53**	0.4	12.0	0.9	G2V^p	191
HD 23478	3:43:32.0	32:08:08	32	1.5	6.7	0.9	B3IV...	451
Joshi 18	3:43:38.0	32:27:00	32	0.7	9.3	0.8	F2V^p	1132
Il'in 5	3:44:17.0	33:10:12	24	0.8	9.7	1.3	B9.5III^p	552
HD 23606	3:44:34.6	34:51:53	101	0.9	9.5	0.9	B8.5V^p	525
HD 23625	3:44:41.0	33:26:48	19	0.6	6.6	1.1	B2.5V	342
HD 23802	3:45:58.3	32:06:44	50	1.4	7.4	0.9	B5v	322
HD 23974	3:47:19.4	31:24:11	65	1.9	8.6	1.4	B 6V^p	236
HD 24131	3:48:41.5	34:12:35	95	0.9	5.8	1.0	B0.5V	496
HD279128	3:49:05.4	33:15:27	83	1.4	8.9	1.4	A0II	1253

Notes:
Spectral classification and distances are based on spectroscopic data where available. Sp. class. marked with ^p are based on Vilnius photometry from Cernis (1993)

Table 2

Best fitting parameters to Q & U forBD+31 "643

	Serkowski-Wilking relation	Serkowski-Wilking + Rayleigh
P_{max}	1.45 ±0.03	1.45*0 .03
λ_{max}	0.67±0.02	0.67±0.01
K	2.3±0.3	3.6± 0.7
c		0.008*0.002
θ_S	-34.7±0.01	-35.6±0.01
θ_R		-14.7±0.1
$\chi^{2\dagger}$	6.4	2.1

Notes:

† Per degree of freedom

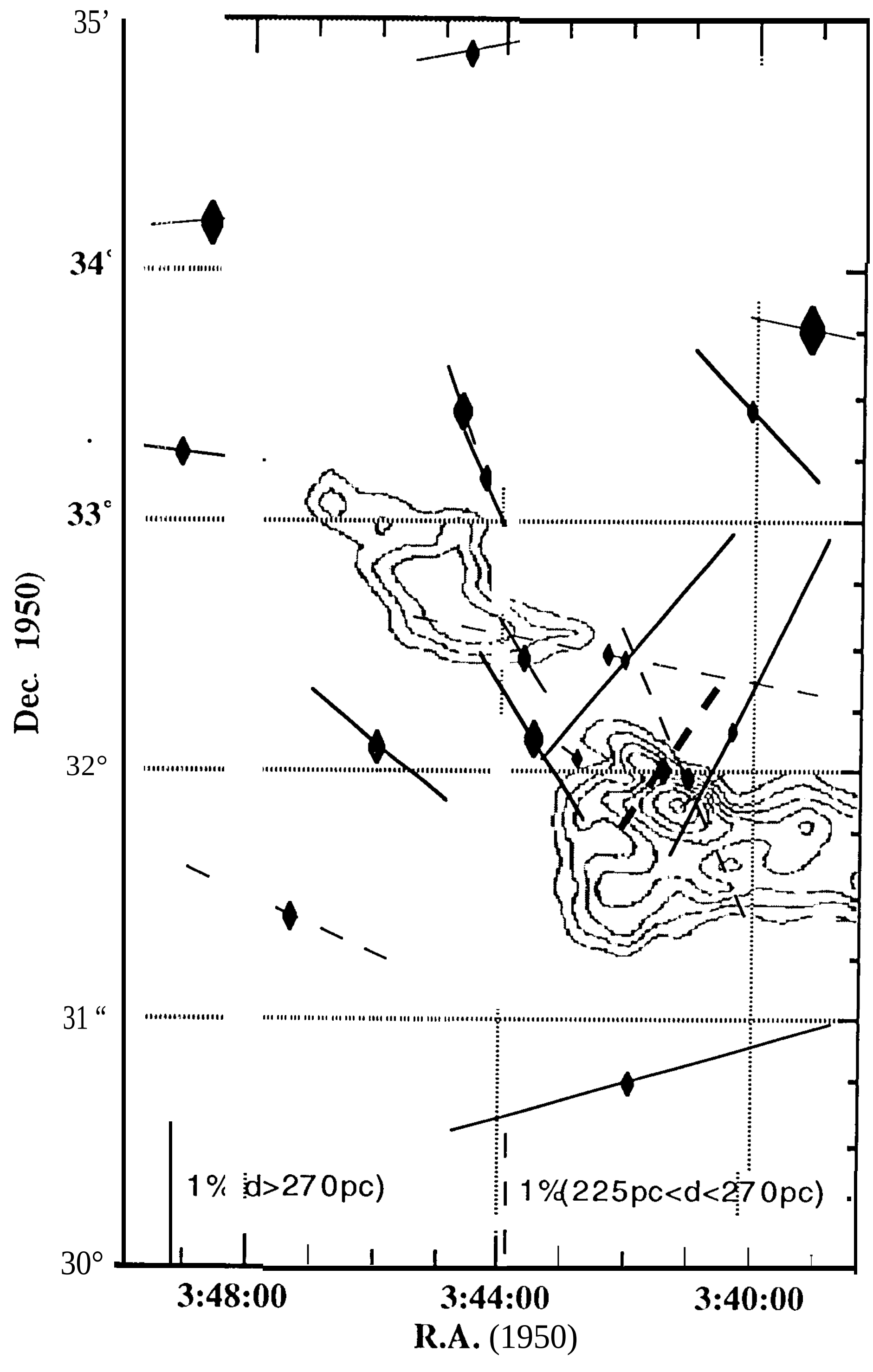
Figure Captions

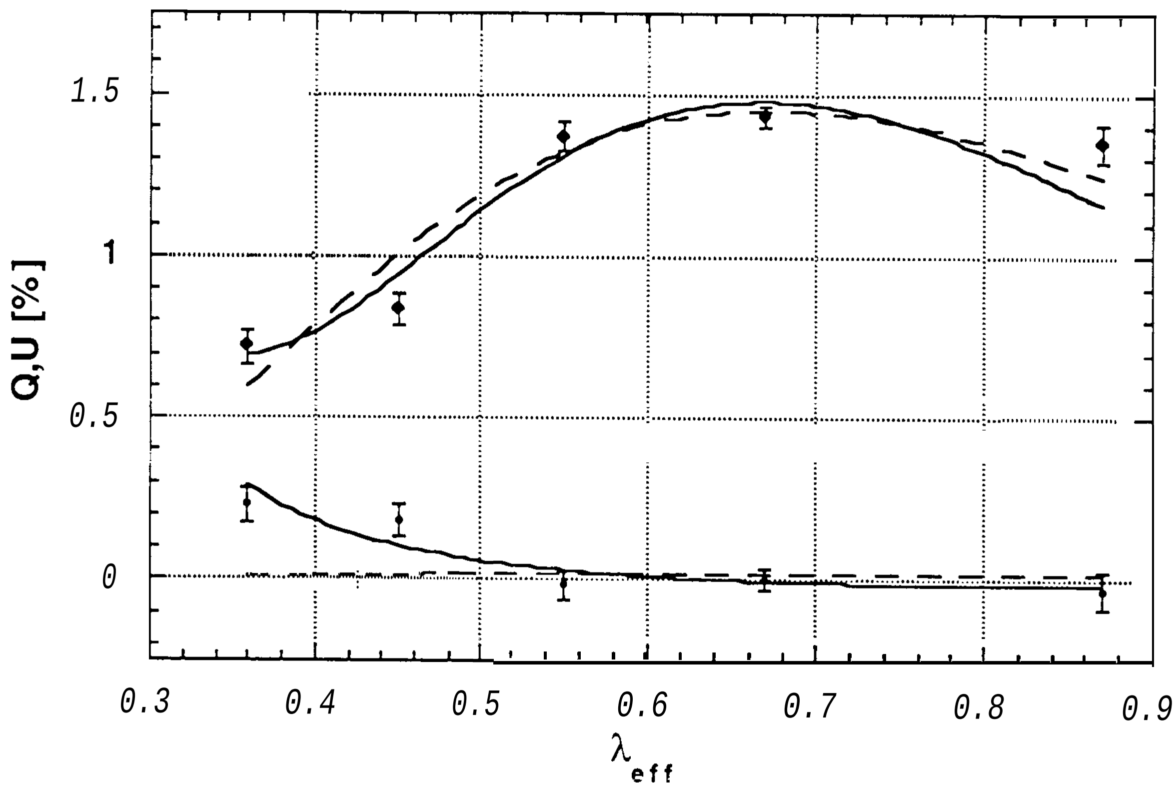
Figure 1,

The polarizations of stars in the vicinity of IC348 shows a magnetic field running NE-SW. The size of the diamonds are inversely proportional to the magnitude of each star, while the length of the bar is proportional to the measured magnetic field. The orientation of the bars show the direction of the magnetic field at each location. Solid bars are for stars background to the cloud whereas dashed bars are for stars at the approximate distance of the cloud. The heavy dashed bar is for BD+3 10643. Note that both of the two "anomalous" stars are photometrically classified, faint, red giants.

Figure 2.

The normalized Q & U measurements are simultaneously fitted by a Serkowski-Wilking relation (dashed curves) and a combination of a Serkowski-Wilking relation and a Rayleigh scattering term (solid curve). While the Q measurements can be equally well fitted by either function, the U measurements are clearly better fitted by the second,


35'
34°
33°
32°
31°
30°
Dec. 1950)
1% d>270pc)
1%(225pc<d<270pc)
3:48:00
3:44:00
3:40:00
R.A. (1950)


1.5
1
0.5
0
Q,U [%]
0.3
0.4
0.5
0.6
0.7
0.8
0.9
λ_{eff}