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OPTICAL POLARIZATION OF SOLAR TYPE STARS WITH DEBRIS DISKS

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RESUMEN

Se presentan mediciones polarimétricas en el óptico de 34 estrellas de secuencia principal con discos de escombros observables desde el hemisferio sur, junto con 54 estrellas sin evidencia de disco. Estas muestras se combinan con una de 109 estrellas del hemisferio norte de la literatura, para obtener dos conjuntos de 51 y 97 estrellas de tipo solar con y sin disco, respectivamente. Los valores de polarización de ambas muestras no resultan estadísticamente diferentes dentro de la precisión alcanzada. Sin embargo, se identifican 9 estrellas ($d \lesssim 50$ pc) con disco que poseen valores de polarización por encima de la media de la muestra con disco y que no reproducen adecuadamente la ley interestelar de Serkowski. Estas estrellas son candidatas a poseer polarización intrínseca. En este caso los discos de escombros de estas estrellas podrían estar poblados por partículas con tamaños de $\approx 0.1\mu$m.

ABSTRACT

We report optical aperture polarimetry for 34 southern hemisphere main-sequence stars with debris disks, in addition to 54 stars without evidence of disk. These sets of stars are combined with another set of 109 stars from the northern hemisphere, obtained from the literature, to build two samples of 51 and 97 solar-type stars with and without debris disks. The distributions of polarization values for the samples with and without disks show no significant statistical difference, within the precision of our observations. However, we identify a sub-sample of 9 stars ($d \lesssim 50$ pc) with disks that have polarization levels above the median for the sample with disk, and that are not appropriately reproduced by Serkowski's interstellar law. These stars are candidates to have intrinsic polarization. In this case the debris disks in these stars may be populated by small dust with sizes of $\approx 0.1\mu$m.

Key Words: Kuiper belt: general — stars: solar-type — techniques: polarimetric — zodiacal dust

1. INTRODUCTION

Debris disks are circumstellar disks around main-sequence stars (Backman & Paresce 1993). The first debris disks were detected in the 80's as emission excesses, over the stellar continuum, at infrared wavelengths by the *IRAS* satellite (Aumann et al. 1984). Later on, the *Spitzer* mission increased the number of debris disk stars, particularly among solar-type (see, for example, Bryden et al. 2006) and binary stars (Trilling et al. 2007).

In addition to producing emission excesses at infrared wavelengths, the dust is capable of polarizing the stellar radiation. In the 60's polarized light was observed from young stellar objects (YSO's, Vardanian 1964; Serkowski 1969), as result of the scattering produced by dust particles in circumstellar disks (Bastien & Landstreet 1979).

The coronagraphic technique has allowed to obtain optical polarization maps of two well-known debris disks: β Pictoris (β Pic, Gledhill et al. 1991; Wolstencroft et al. 1995; Tamura et al. 2006) and AU Microscopii (AU Mic, Graham et al. 2007). The degree of polarization varies with the radial distance to the star. In the case of AU Mic, the variation ranges from $\approx$5% (at 20 AU) to $\approx$40% (at 80 AU). For β Pic, polarization levels range from $\approx$10% to

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$\approx 25\%$. The stellar light is polarized perpendicular to the radial direction and the polarization pattern is symmetric around the central star. This supports the assumption that the radiation from the central source is being single-scattered by small spherical dust grains ($x = 2\pi a/\lambda \lesssim 1$, with a the grain radius), in an optically thin disk.

Aperture polarimetry of stars with debris disks has been also reported in the literature (Bhatt & Manoj 2000; Oudmaijer et al. 2001; Eritsyan et al. 2002; Chavero et al. 2006). The levels of polarization found range from $\approx 0.1\%$ to $\lesssim 2\%$. These values are significantly lower than those found when the disk radiation can be distinguished from the light of the star, as is the case of coronagraphic polarimetry observations. These surveys show a correlation between the polarization level and the ratio $L_{\rm IR}/L_{\rm star}$ (Bhatt & Manoj 2000; Yudin 2000): stars with higher values of $L_{\rm IR}/L_{\rm star}$ (i.e., higher infrared emission excesses) have higher values of optical polarization. This correlation supports an intrinsic origin for the observed polarized radiation.

We have measured aperture polarizations at the $BVRI$ bands for 88 southern hemisphere main-sequence stars with spectral types FGK, with and without disks. Our objective is to characterize the optical polarization of solar-type stars with debris disks and to search for differences with the polarizations of stars without disks. The sample and data acquisition are described in § 2. In § 3 we combine our sample with northern hemisphere stars from (Simon 2010) to carry out a statistical comparison of the measured polarizations for stars with and without disks. For the sample with disk, we identified a sub-sample of 9 objects with polarization levels above the median and discuss the properties of the dust particles in these disks in § 4. Finally in § 5, we summarize the results and present our conclusions.

2. THE OBSERVATIONS

We selected two samples, observable from the southern hemisphere: stars with infrared excesses detected by *Spitzer* (34 objects) and stars with no evidence of emission excesses at the *Spitzer* wavelengths (54 objects). In the selection procedure we gave priority to solar-type stars with large emission excesses (although some A and M stars were also included). Strong excess emissions are indicative of higher dust mass. Stars with ages $< 10^7$yr were excluded.

The observations were obtained with the instruments FOTOR and CASPROF attached to the 2.15 m Jorge Sahade telescope at the Complejo Astronómico El Leoncito (CASLEO), San Juan, Argentina. These are photoelectric aperture polarimeters equipped with a half-wave plate retarder and a Wollaston prism. The data were gathered from 2007 to 2012.

Each target was observed in the $BVRI$ bands. The data acquisition with FOTOR was made with a $15''$ diaphragm and all bands were observed simultaneously. In the case of CASPROF, an aperture of $17''$ was used and the observations were made in one band at time. A typical observation sequence consisted of 8 integrations with exposure times of 60-120 s, depending on the stellar magnitude and weather conditions at the moment of observation. Each target was observed twice every night and therefore they have, at least, 16 minutes of integration in each band. At the beginning of every observation, the sky was observed first to eliminate its contribution. We checked the count levels between observations and discarded any data with signs of poor sky conditions. In addition, two polarimetric standards from (Hsu & Breger 1982) and (Schmidt et al. 1992) were observed each night to check the instrument.

To combine observations from FOTOR and CASPROF, we used polarimetric data of targets observed with both instruments to define a linear transformation to put FOTOR data on the CASPROF scale. Polarization values for the stars with debris disks are presented in Table 1 and for the stars without disks in Table 2. Errors were estimated using the following expression: $\sigma_\lambda = \sqrt{(\Delta F_\lambda^{\rm obj} F_\lambda^{\rm obj})^2 + (\Delta F_\lambda^{\rm sky} F_\lambda^{\rm sky})^2}$, where, $\mathrm{F}_\lambda^{\rm obj}$ and $\mathrm{F}_\lambda^{\rm sky}$ are the fluxes of the object and the sky, repectively. $\Delta F_\lambda^{\rm obj}$ and $\Delta F_\lambda^{\rm sky}$ are the averages of individual measurements for each object. We achieved a mean precision of 0.035% for the observed polarizations.

Polarizations for ≈ 40 stars in our samples have been previous reported by (Leroy 1993) and (Heiles 2000). Figure 1 shows the differences between our polarizations and those from the literature ($\mathrm{P_{Cas} - P_{Lit}}$) vs. V magnitude. These differences have an average dispersion, $\sigma = 0.03$, in good agreement with the mean precision of our observations.

The star HD 121504B (classified as without disk) shows the highest values of polarization ($\approx 2\%$ in V) among the observed targets. However, this is probably a background object not gravitationally bound to HD 121504. Its small proper motion ($\mu_\alpha cos\delta = -18$ mas/yr, $\mu_\delta = 4$ mas/yr)

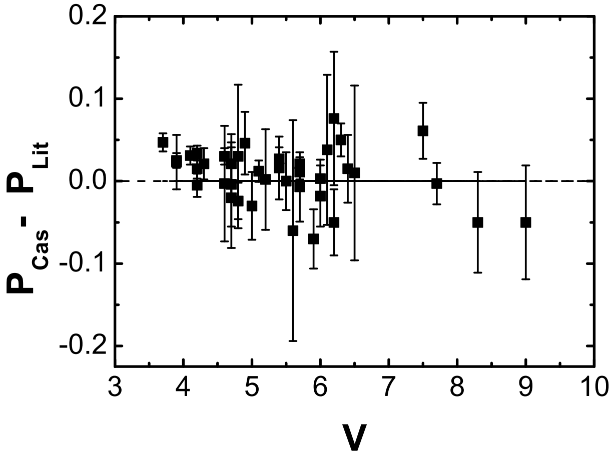

Fig. 1. Differences between our polarization measurements and those reported in the literature for ≈ 40 stars in our sample.

differs from proper motion of HD 121504 $\mu_\alpha cos\delta = -248$ mas/yr, $\mu_\delta = -86$ mas/yr; (Mason et al. 2001). HD 121504B was eliminated from our analysis.

3. STATISTICAL COMPARISON

To increase the size of our samples, we combined our targets with 109 stars observed by (Simon 2010) in the northern hemisphere. Northern stars were observed with the photoelectric polarimeter "La Belle et la Bête," (Manset & Bastien 1995) attached to the 1.6 m telescope of the Mont-Mégantic observatory, in Quebec, Canada. The aperture for all observations was of 8.18″. Accuracy levels range from 0.02 to 0.12%, with a mean value of 0.04%. We searched in the literature for evidence of disks in Simon's sample and classified 20 stars as "with disk" and 48 stars as "without disk". For the remaining 41 stars, no evidence supporting or rejecting the presence of debris disks was found and thus they were not included.

The stars in Simon's sample were observed with a broad-band filter with $\lambda_{\rm eff} = 0.77$ μm and FWHM ≈0.24 μm. To combine our sample with the northern sky star data, we averaged the polarization in the R and I bands, since the $\lambda_{\rm eff}$ of the filter used by (Simon 2010) lies between the R and I bands.

We selected stars with $d \lesssim 50$ pc, as the interstellar polarization is negligible within this distance (Leroy 1993). With this restriction we ended up with a total of 51 stars with debris disks, and 97 without disks, combining the southerns and northern sky samples.

Figure 2 shows the cumulative distributions for the polarization of the 51 stars with debris disks and the 97 stars without disks. The medians are 0.040% and 0.036% respectively, and they turn out to be indistinguishable, considering the precision of the observations ($\Delta P \approx 0.035\%$). The statistical Kolmogorov-Smirnov test (Press et al. 1992) gives a probability of 0.6 that both samples represent the same population of objects. Within the precision of our observations, there are no significant differences between the polarization levels of the samples with and without debris disks. The data in BV-bands from FOTOR and CASPROF were also analyzed and they show the same tendencies.

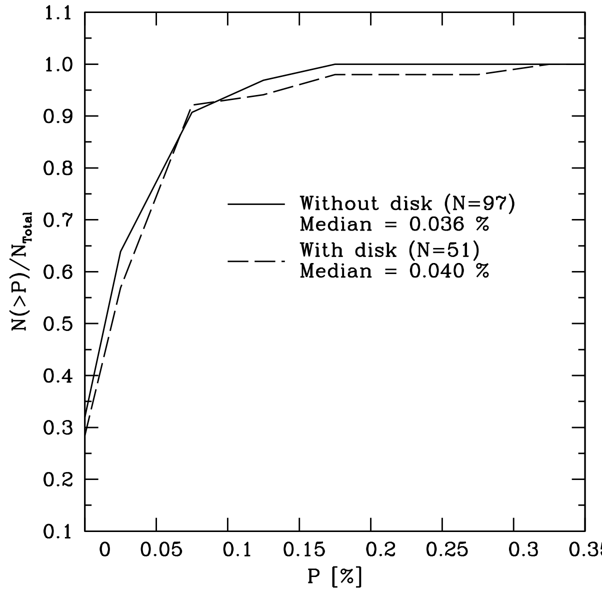

Fig. 2. Cumulative distributions for the measured polarizations of stars with disk (dashed-line) and without disk (solid-line).

Earlier investigations of T Tauri stars, showed a decrease in the degree of optical polarization with age. Stars with ages of ≈ 10^6 yr have typical polarization values of ≈ 2%, while stars with ages of ≈ 10^7 yr have polarizations $\lesssim$ 2% (Bastien 1996). Lower polarization levels are expected for debris disk stars. This is consistent with the current theory of planet formation. As circumstellar disks evolve, the dust goes through transformation processes which lead to the formation of larger objects that concentrate most of the mass. Eventually, evolved circumstellar disks would be devoid of small particles ($< 1\,\mu$m). If little dust (capable of efficiently scattering optical radiation) is left over in the disk, the intensity of the polarized radiation will be lower and harder to detect than in younger stars.

TABLE 1

OPTICAL POLARIZATIONS OF THE STARS WITH DEBRIS DISKS

Star	d [pc]	V	P_B [%]	P_V [%]	P_R [%]	P_I [%]	Instrument[a]	N. Nights	Date
HD 105	40.2	7.5	0.088±0.007	0.092±0.005	0.080±0.005	0.017±0.005	CASPROF	4	2009–2010
HD 2262	42.5	3.9	0.075±0.009	0.035±0.008	0.061±0.007	0.050±0.005	CASPROF	4	2009–2010
HD 10008	23.6	7.6	0.066±0.007	0.043±0.003	0.052±0.002	0.048±0.003	CASPROF	4	2009–2010
HD 10647[b]	17.3	5.5	0.096±0.007	0.040±0.004	0.012±0.003	0.020±0.003	CASPROF	3	2009–2010
HD 17925	10.4	6.0	0.094±0.006	0.029±0.003	0.020±0.002	0.023±0.002	CASPROF & FOTOR	8	2008–2010
HD 20320	36.8	4.8	0.074±0.007	0.029±0.005	0.020±0.011	0.015±0.006	CASPROF	4	2009–2011
HD 20631	36.6	5.4	0.087±0.014	0.046±0.010	0.008±0.005	0.012±0.005	CASPROF	2	2009
HD 22049[b]	3.2	3.7	0.048±0.009	0.054±0.004	0.053±0.005	0.049±0.008	CASPROF	3	2009–2010
HD 31392	25.9	7.6	0.114±0.006	0.023±0.003	0.186±0.003	...	CASPROF	2	2009
HD 33262	11.6	4.7	0.07±0.05	0.01±0.05	0.01±0.04	0.04±0.07	FOTOR	4	2008
HD 35850[b]	26.8	6.3	0.080±0.014	0.058±0.012	0.015±0.008	...	CASPROF	2	2011
HD 69830[b]	12.6	5.9	0.118±0.020	0.010±0.008	0.022±0.004	0.007±0.002	CASPROF & FOTOR	8	2007–2009
HD 76151	17.1	6.0	0.221±0.044	0.032±0.013	0.089±0.013	0.070±0.014	CASPROF	4	2009 & 2012
HD 82943[b]	27.4	6.5	0.113±0.013	0.052±0.007	0.013±0.008	0.048±0.012	CASPROF	9	2009–2012
HD 92945	21.6	8.6	0.090±0.007	0.083±0.004	0.087±0.003	0.076±0.004	CASPROF & FOTOR	10	2007–2009
HD 95698	53.1	6.2	0.075±0.006	0.012±0.003	0.019±0.004	0.010±0.005	CASPROF & FOTOR	11	2008–2012
HD 105211	19.7	4.1	0.039±0.013	0.054±0.008	0.054±0.007	0.025±0.009	CASPROF & FOTOR	4	2007 & 2009
HD 105912	50.2	6.9	0.056±0.091	0.186±0.055	0.274±0.043	0.414±0.032	CASPROF	1	2010
HD 109085	18.2	4.3	0.035±0.017	0.032±0.011	0.042±0.005	0.025±0.006	CASPROF	4	2010–2012
HD 115617[b]	8.5	4.7	0.072±0.015	0.051±0.008	0.057±0.009	0.057±0.006	CASPROF	5	2009
HD 118972	15.6	6.9	0.115±0.006	0.031±0.005	0.017±0.004	0.013±0.003	CASPROF	5	2010–2011
HD 139664	17.5	4.6	0.12±0.05	0.02±0.07	0.00±0.06	0.03±0.06	FOTOR	1	2007
HD 141943	133	7.8	0.107±0.027	0.018±0.015	0.031±0.007	0.004±0.008	CASPROF	12	2009–2012
HD 191089	53.5	7.2	0.101±0.007	0.067±0.003	0.066±0.004	0.084±0.004	CASPROF	6	2009–2010
HD 191408	6.0	5.3	0.04±0.02	0.02±0.02	0.00±0.03	0.03±0.04	FOTOR	6	2007–2008
HD 197481	9.9	8.6	0.049±0.018	0.027±0.005	0.049±0.002	0.067±0.002	CASPROF	5	2009–2010
HD 199260	21.0	5.7	0.090±0.008	0.037±0.004	0.014±0.003	0.005±0.004	CASPROF	2	2009
HD 199532	45.3	5.1	0.09±0.04	0.09±0.07	0.07±0.09	0.13±0.10	FOTOR	5	2007–2008
HD 202917	45.8	8.7	0.108±0.010	0.044±0.005	0.009±0.004	0.015±0.007	CASPROF	3	2009 & 2011
HD 207129	15.6	5.6	0.089±0.005	0.035±0.002	0.013±0.002	0.010±0.003	CASPROF	5	2009–2010
HD 209253	30.1	6.6	0.071±0.006	0.020±0.004	0.003±0.003	0.023±0.003	CASPROF	5	2009–2011
HD 210277[b]	21.3	6.6	0.04±0.03	0.09±0.08	0.08±0.08	0.08±0.10	FOTOR	4	2007–2008
HD 217792	28.6	5.1	0.107±0.004	0.025±0.004	0.018±0.003	0.010±0.003	CASPROF & FOTOR	4	2009 & 2011
HD 219482	20.6	5.7	0.07±0.03	0.05±0.09	0.05±0.06	0.07±0.07	FOTOR	5	2007–2008

[a]Polarizations listed for FOTOR are transformed to CASPROF scale.
[b]Stars with known extrasolar planets.

In addition, the intensity of the measured polarization depends on the orientation between the plane of the disk and the direction to the observer. Emerging polarization will be reduced by a factor $\sin^2(i)$ (i is the angle between the axis of symmetry of the disk and the direction to the observer) when $i \neq 90^o$ (Bastien 1987).

The measured polarization levels for debris disks stars are significantly higher when the unpolarized radiation from the star is blocked. For example, (Graham et al. 2007) found P (in the V-band) varying between 5% to 40% (depending on the radial distance to the star) for the star AU Mic (HD 197481) using coronagraphic techniques. We measured $P = 0.027 \pm 0.005\%$ for this star. Also with the coronagraphic technique, (Gledhill et al. 1991) measured $P \approx 17 \pm 3\%$ in the R-band for β Pic. (Krivova et al. 2000) estimated $P \approx 0.24 \pm 0.011\%$ when the unpolarized radiation from the star is not blocked. The large amount of unpolarized stellar radiation may hide the smaller fraction of polarized radiation from the disk (Simon 2010).

4. INDIVIDUAL STARS

The statistical comparison discussed in § 3 allowed us to identify a sub-sample of stars with disk and observed polarizations $P_\lambda^{\rm obs} > \bar{P}_\lambda + 3\sigma_\lambda$, where $\bar{P}_\lambda$ is the median polarization of the objects with disks, and σ_λ the precision on $P_\lambda^{\rm obs}$ with a given filter. This sub-sample is listed in Table 3. These targets are considered candidate intrinsic polarization stars, that lie within a distance of $\lesssim 50$ pc, where the interstellar contribution to the measured polarization is negligible (Leroy 1993).

In a previous work (Chavero et al. 2006) measured optical polarization of a sample of 39 *IRAS* selected debris disk stars of spectral types earlier than those reported in this work. They identified

TABLE 2

OPTICAL POLARIZATIONS OF THE STARS WITHOUT DEBRIS DISK

Star	d [pc]	V	P_B [%]	P_V [%]	P_R [%]	P_I [%]	Instrument[a]	N Nights	Date
HD 142[b]	25.6	5.7	0.070±0.004	0.029±0.003	0.017±0.003	0.024±0.005	CASPROF & FOTOR	10	2007–2011
HD 739	21.8	5.2	0.02±0.03	0.01±0.06	0.00±0.04	0.04±0.01	FOTOR	2	2007
HD 1237[b]	17.6	6.6	0.11±0.06	0.06±0.06	0.04±0.05	0.10±0.09	FOTOR	3	2007
HD 4391	14.9	5.8	0.11±0.01	0.09±0.03	0.02±0.02	0.01±0.02	FOTOR	2	2007
HD 6434	40.3	7.7	0.02±0.01	0.03±0.01	0.03±0.07	0.05±0.02	FOTOR	2	2007
HD 10360	8.1	5.9	0.25±0.09	0.17±0.10	0.15±0.15	0.21±0.16	FOTOR	5	2007–2008
HD 13445[b]	10.8	6.2	0.05±0.07	0.08±0.08	0.02±0.05	0.12±0.11	FOTOR	1	2007
HD 16141[b]	38.9	6.8	0.10±0.01	0.17±0.06	0.12±0.07	0.10±0.09	FOTOR	2	2007
HD 20794	6.0	4.2	0.07±0.01	0.00±0.01	0.00±0.01	0.01±0.01	FOTOR	2	2008
HD 23754	17.9	4.2	0.032±0.011	0.040±0.006	0.035±0.005	0.049±0.005	CASPROF & FOTOR	8	2008–2011
HD 31925	43.2	5.7	0.04±0.04	0.00±0.04	0.00±0.04	0.05±0.07	FOTOR	1	2008
HD 38392	9.0	6.1	0.20±0.11	0.05±0.09	0.15±0.12	0.05±0.09	FOTOR	1	2008
HD 39891	56.0	6.3	0.05±0.08	0.00±0.03	0.00±0.03	0.02±0.05	FOTOR	1	2008
HD 43162	16.7	6.4	0.04±0.05	0.00±0.03	0.01±0.04	0.00±0.05	FOTOR	1	2008
HD 51733	38.5	5.5	0.03±0.06	0.06±0.08	0.01±0.07	0.11±0.10	FOTOR	1	2008
HD 62644	24.1	5.0	0.03±0.08	0.00±0.04	0.00±0.03	0.02±0.07	FOTOR	1	2008
HD 68456	21.4	4.8	0.11±0.05	0.09±0.08	0.01±0.06	0.04±0.09	FOTOR	1	2008
HD 70958	27.2	5.6	0.07±0.09	0.03±0.06	0.01±0.10	0.03±0.09	FOTOR	1	2008
HD 73526[b]	94.6	9.0	0.083±0.027	0.115±0.007	0.111±0.007	0.112±0.009	CASPROF	1	2009
HD 75289[b]	28.9	6.4	0.10±0.08	0.02±0.05	0.04±0.05	0.09±0.14	FOTOR	1	2007
HD 84117	14.8	8.3	0.06±0.06	0.00±0.05	0.00±0.03	0.01±0.07	FOTOR	1	2008
HD 88745	···	10.7	0.139±0.011	0.170±0.009	0.160±0.009	0.150±0.014	CASPROF	6	2010–2012
TYC7708-2185-1	···	11.6	0.195±0.023	0.084±0.017	0.117±0.014	0.102±0.020	CASPROF	3	2010–2012
HD 92139	26.5	3.8	0.06±0.01	0.04±0.03	0.00±0.03	0.09±0.01	FOTOR	2	2008
HD 97698	174.8	7.1	0.10±0.02	0.077±0.010	0.034±0.011	0.013±0.011	CASPROF	1	2009
HD 99492[b]	17.9	7.5	0.00±0.01	0.07±0.03	0.10±0.05	0.02±0.07	FOTOR	1	2007
HD 102365	9.2	4.9	0.096±0.041	0.096±0.015	0.038±0.008	0.103±0.008	CASPROF	3	2010–2012
HD 109749[b]	59.0	8.1	0.06±0.02	0.06±0.05	0.03±0.07	0.13±0.04	FOTOR	2	2007–2008
HD 114729[b]	35.0	6.7	0.11±0.12	0.05±0.10	0.00±0.03	0.12±0.08	FOTOR	1	2007
HD 121504[b]	44.4	7.6	0.093±0.005	0.074±0.004	0.070±0.004	0.080±0.003	CASPROF & FOTOR	11	2007–2012
HD 121504B	···	9.4	1.896±0.016	2.068±0.008	2.003±0.008	1.721±0.007	CASPROF	3	2012
HD 129502	18.7	3.9	0.163±0.014	0.061±0.010	0.039±0.005	0.064±0.007	CASPROF	3	2009–2012
HD 134987[b]	25.6	6.5	0.13±0.11	0.04±0.10	0.07±0.06	0.07±0.07	FOTOR	1	2007
HD 136352	14.5	5.6	0.064±0.015	0.063±0.013	0.021±0.010	0.041±0.006	CASPROF	5	2010–2011
HD 139664	17.5	4.6	0.103±0.013	0.053±0.007	0.030±0.004	0.055±0.004	CASPROF	10	2009–2010
HD 141397	150.0	8.8	0.12±0.15	0.11±0.10	0.07±0.12	0.07±0.13	FOTOR	1	2007
HD 147513	12.9	5.4	0.312±0.031	0.056±0.015	0.074±0.019	0.050±0.008	CASPROF & FOTOR	6	2007–2012
HD 154088	18.1	6.6	0.07±0.07	0.00±0.05	0.00±0.05	0.07±0.11	FOTOR	1	2007
HD 160032	21.9	9.0	0.01±0.07	0.00±0.06	0.00±0.06	0.01±0.03	FOTOR	1	2007
HD 160691[b]	15.3	5.1	0.02±0.02	0.03±0.03	0.00±0.03	0.05±0.12	FOTOR	3	2007
HD 165499	17.8	5.5	0.02±0.04	0.03±0.10	0.05±0.09	0.08±0.09	FOTOR	1	2007
HD 168443[b]	37.9	6.9	0.17±0.14	0.07±0.12	0.09±0.10	0.13±0.11	FOTOR	3	2007
HD 169830[b]	36.3	5.9	0.17±0.10	0.16±0.13	0.11±0.12	0.21±0.10	FOTOR	1	2007
HD 177565	17.2	6.2	0.22±0.10	0.01±0.01	0.10±0.07	···	CASPROF	2	2010–2012
HD 179949[b]	27.0	6.2	0.04±0.07	0.03±0.02	0.00±0.02	0.06±0.10	FOTOR	2	2007
HD 181321	20.8	7.0	0.07±0.04	0.04±0.03	0.02±0.02	0.05±0.03	FOTOR	2	2007
HD 188376	23.8	4.7	0.21±0.15	0.01±0.05	0.00±0.05	0.04±0.07	FOTOR	2	2007
HD 189567	17.7	6.1	0.101±0.006	0.039±0.004	0.026±0.004	0.014±0.004	CASPROF & FOTOR	6	2008–2010
HD 196050[b]	46.9	7.5	0.06±0.02	0.08±0.12	0.02±0.11	0.09±0.04	FOTOR	2	2007
HD 203608	9.2	4.2	0.02±0.04	0.03±0.01	0.01±0.05	0.07±0.09	FOTOR	3	2007
HD 212697	20.1	6.4	0.08±0.05	0.03±0.04	0.03±0.05	0.07±0.01	CASPROF & FOTOR	8	2008–2010
HD 213240[b]	40.7	6.8	0.06±0.02	0.09±0.12	0.04±0.09	0.12±0.06	FOTOR	2	2007
HD 216437[b]	26.5	6.1	0.04±0.03	0.01±0.02	0.01±0.02	0.08±0.06	FOTOR	3	2007
HD 222582[b]	41.9	6.4	0.067±0.003	0.035±0.003	0.031±0.001	0.029±0.003	CASPROF & FOTOR	8	2007–2011

[a]Polarizations listed for FOTOR are transformed to CASPROF scale.
[b]Stars with known extrasolar planets.

6 systems whose polarizations may not be related to the interstellar medium. (Simon 2010) detected only one star (HD 115404) with polarization $P \geq 3\sigma$ and three stars with $2\sigma < P < 3\sigma$. These works show the difficulties of detecting polarized radiation of debris disks with the current instrumentation.

TABLE 3

STARS WITH POLARIZATIONS ABOVE THE MEDIAN FOR THE SAMPLE WITH DEBRIS DISKS

Star	P_B %	P_V %	P_R %	P_I %
HD 105	0.088±0.007	0.092±0.005	0.080±0.005	0.017±0.005
HD 10008	0.066±0.007	0.043±0.003	0.052±0.002	0.048±0.003
HD 22049	0.048±0.009	0.054±0.004	0.053±0.005	0.049±0.008
HD 31392	0.114±0.006	0.023±0.003	0.186±0.003	···
HD 92945	0.090±0.007	0.083±0.004	0.087±0.003	0.076±0.004
HD 105912	0.056±0.091	0.186±0.055	0.274±0.043	0.414±0.032
HD 109085	0.027±0.009	0.028±0.009	0.057±0.003	0.035±0.005
HD 197481	0.049±0.018	0.027±0.005	0.049±0.002	0.067±0.002
HD 217792	0.107±0.004	0.025±0.004	0.018±0.003	0.010±0.003
HD 121504 B	1.896±0.016	2.068±0.008	2.003±0.008	1.721±0.007

The Serkowski law (Serkowski 1973) is an empirical relation that reproduces the wavelength dependence of the interstellar linear polarization in the optical range,

$$P_\lambda = P_{\max} exp[-K ln^2(\lambda_{\max}/\lambda)], \qquad (1)$$

where $P_{\max}$ is the maximum polarization at the wavelength $\lambda_{\max}$ and K determines the shape of the curve. Typical K values for the interstellar medium range from $\approx$ 0.6 to 2.0 (see for example, Whittet et al. 1992; Weitenbeck 2004).

We applied Serkowski's law as an additional criterion to identify stars listed in Table 3 as candidate non-interstellar (or intrinsic) polarization objects. As we mention at the end of this section, the confirmation of these candidates requires follow-up observations, such as high resolution coronagraphic images. Nevertheless, this analysis may point to interesting targets to search for debris disks with optical intrinsic polarization.

We performed two fits to the objects listed in Table 3, with $K = 1.15$, as originally proposed by Serkowski, and with K variable. The best sets of parameters were determined through the minimization of χ^2 and are listed in Table 4. Figure 3 shows the fitted curves to the observed polarizations.

In general, K is poorly defined for most of the targets (see Table 3) with the exception of HD 121504B. The value of $K = 1.46 \pm 0.08$ is well inside of the range expected for interstellar polarization. This fact and the relatively small proper motion of the star (§ 3), lead us to conclude that the polarization for HD 121504B is of interstellar origin.

For the remaining stars, determining the curvature of Serkowski's law is rather difficult. For example, K takes a value close to 0 and thus $\lambda_{\max}$ is highly undetermined, for HD 10008, HD 22049 and HD 92945. For other stars, K may lie outside of the standard range (for example HD 105 and HD 109085). Finally, in some cases $\lambda_{\max}$ may lie outside the range plotted in Figure 3 (such as: HD 31392, HD 105912, HD 197481 and HD 217792).

The large uncertainties on the values of K, $\lambda_{\max}$ and $P_{\max}$ suggest that Serkowski's law is a poor approximation to the observed polarizations for the objects in our sub-sample. For some stars K takes values outside of the expected range for the interstellar polarization, for others the polarization values are almost constant over the observed range. (Murakawa 2010) found a similar behavior for disks in YSOs, modeled between the B and K bands. The polarization as a function of wavelengths tends to flatten down, particularly at optical wavelengths, for most of the disk scale height (H) and dust grain sizes. The only exception corresponds to a disk model with $H = 1$ and small grains (with $a \approx 0.25\,\mu$m).

The distances ($d \lesssim 50$ pc) to the targets listed in Table 4, as well as the fact that the Serkowski law fails to reproduce the wavelength dependence of the measured polarization, suggest that these polarizations may have an intrinsic origin. If light polarization is produced in debris disks such disks must be populated by dust particles with sizes $\approx 0.1\,\mu$m.

Five of the systems in our sub-sample have additional evidence supporting the existence of small dust particles. For HD 197481 (AU Mic), (Augereau & Beust 2006) showed that dust grains $< 1\,\mu$m are needed to reproduce the brightness profiles at op-

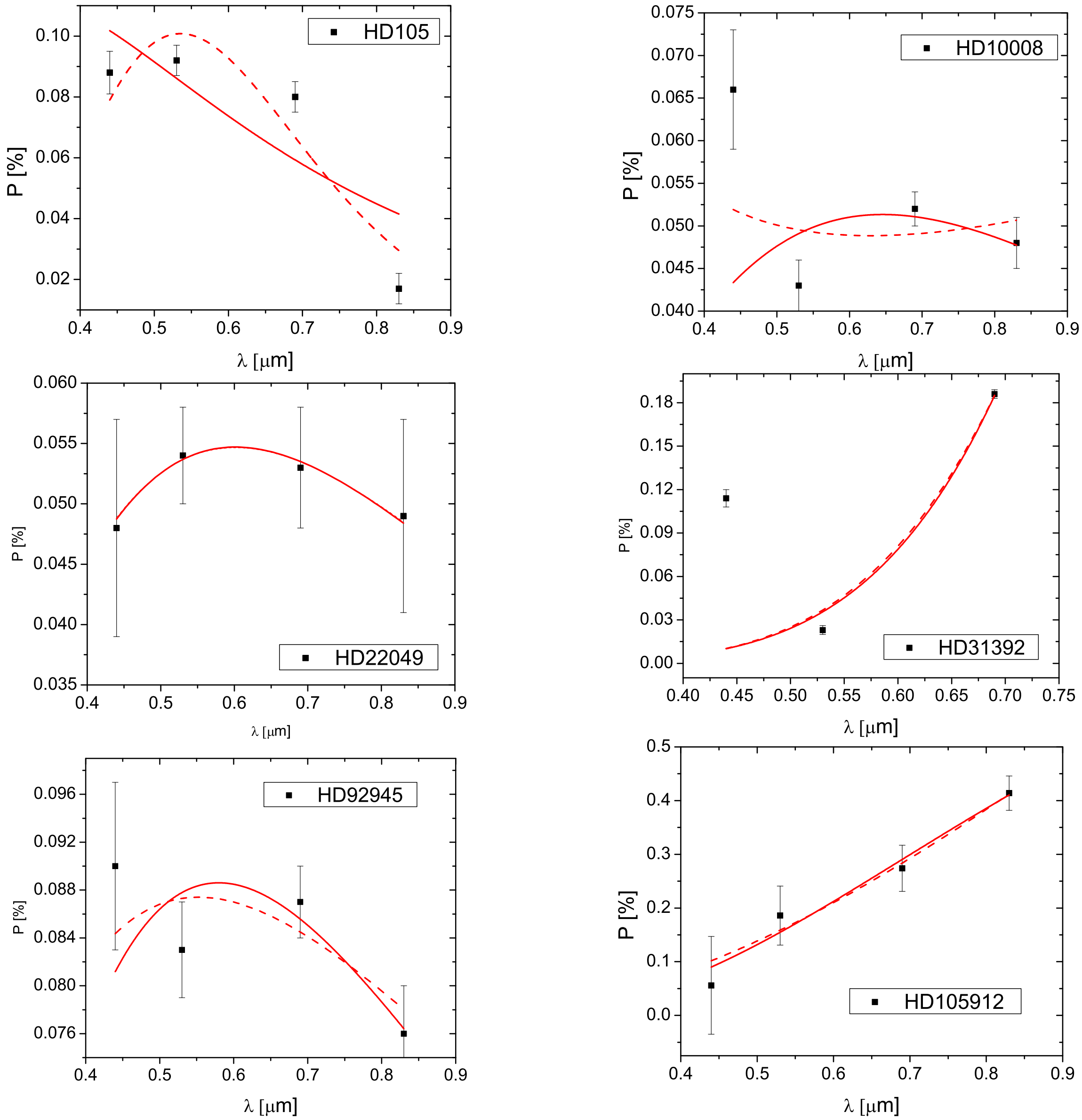

Fig. 3. Serkowski law for the stars with disks and polarization levels above the median. The black squares represent the polarizations in the $\lambda_{\rm eff}$ of $BVRI$ bands, with the corresponding error bars. The solid-line corresponds to the fit with $K = 1.15$, and the dashed-line to the curve treating K as a free parameter.

tical and near-IR wavelengths. The disk around HD 22049 (ϵ Eridanis) may be populated by dust grains with sizes $< 2\,\mu$m (Reidemeister et al. 2011). Optical images of the disk around HD 92945 suggest the existence of sub-micron size dust (Golimowski et al. 2011). For the disk of HD 109085 (η Corvi), the dust grains may have sizes between 0.1 and 100 μm (Lisse et al. 2012).

In the cases of HD 22049 (Backman et al. 2009) and HD 109085 (Lisse et al. 2012), there is evidence of a population of small dust located at ≈ 3 AU from the central star. These disks with "warm" ($T > 100$ K) dust are known in the literature as Exo-Zodiacal systems. About a third of the nearby stars have evidence of exo-zodiacal dust (Bonsor et al. 2013) and modeling of individual systems suggests that they are populated by very small dust grains $a \approx 0.01\,\mu$m, as in the case of Fomalhaut, (Lebreton et al. 2013).

Small dust grains have a short lifetime in debris disks. Collisions grind parent bodies down to dust that is blown out of the system by the radi-

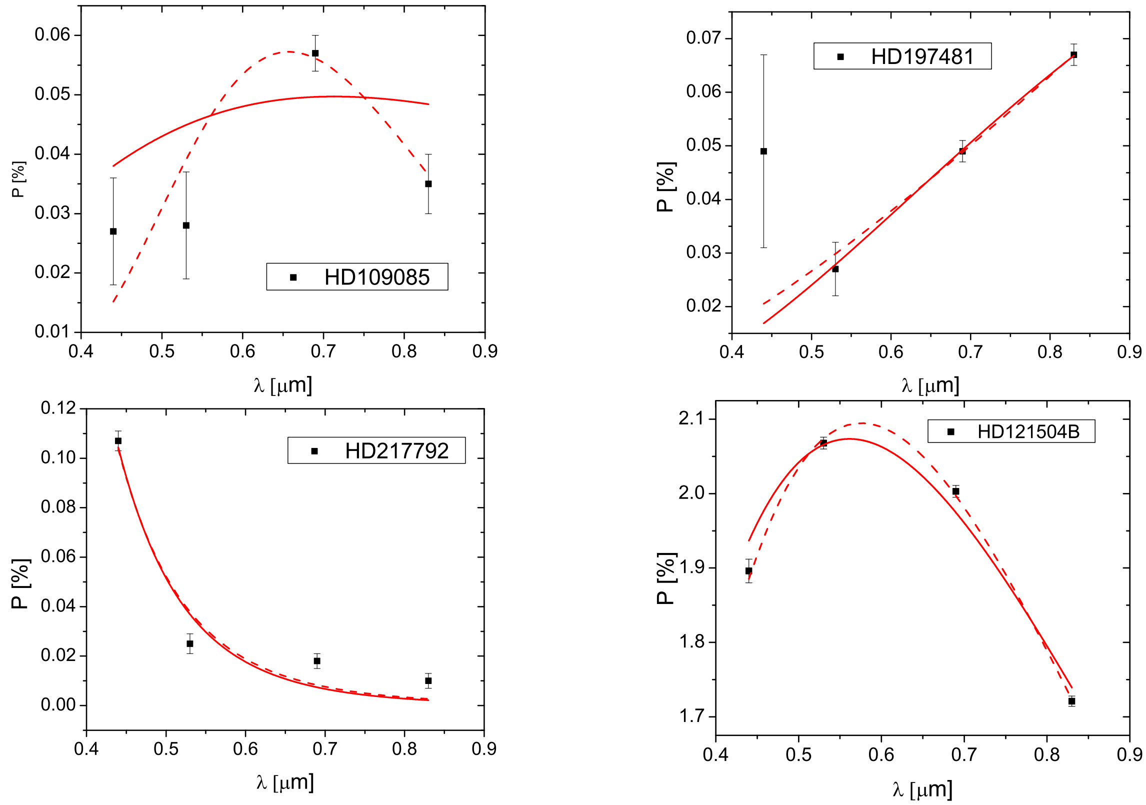

Fig. 3. Continued. Serkowski law fits for the stars with disks and polarization levels above the median.

ation pressure or, that falls onto the star by the Poynting-Robertson drag. Time scales involved in these effects are typically $< 10^6$ yr, much shorter than the age of the star (Krivov 2010). In cold outer debris disks ($T < 100$ K; $R_{\rm disk} > 10$ AU), dust smaller than the critical size may have been recently produced by transient events (such as collisions between massive objects) or may be constantly replentished in a steady-state collisional cascade of large parent bodies. However, the observed levels of warm dust require planetesimal belts so dense that even the largest bodies would have short lifetimes, making their formation in situ unlikely (Wyatt et al. 2007). This has re-motivated the discussions about the origin of the smallest dust particles in debris disks.

The systems identified in § 4 may contain a population of small dust grains in the disks. However, due to the modest polarization levels measured, these values need to be confirmed. High resolution coronagraphic images of the light scattered by this type of dust would be relevant to corroborate the polarization detected, to estimate its location and to help decide whether these debris disks may contain a population of warm small dust particles.

5. SUMMARY AND CONCLUSIONS

We measured the optical polarization for 88 southern sky solar-type stars, 34 of them with debris disks. These objects were combined with 109 northern stars from (Simon 2010) to construct a sample of 51 solar-type stars with debris disks and 97 with no evidence of disks. The median polarization of stars with disk ($\bar{P} \approx 0.040\%$) and without disk ($\bar{P} \approx 0.036\%$) are indistinguishable at the precision level achieved in this work ($\Delta P \approx 0.035\%$).

We identified 9 stars with debris disk and polarization $P_\lambda^{\rm obs} > \bar{P}_\lambda + 3\sigma_\lambda$. The dependence of the polarization with wavelength is not reproduced by Serkowski's interstellar law, suggesting that these stars are candidate intrinsic polarization objects. If this polarization is produced in debris disks, they must contain a population of small dust particles with sizes of ≈ 0.1 μm. Four stars in this sub-sample (AU Mic, Augereau & Beust 2006; ϵ Eridanis, Reidemeister et al. 2011; HD 92945, Golimowski et al. 2011 and η Corvi, Lisse et al. 2012) show additional evidence supporting this conclusion. Due to the short lifetime of the smaller particles, it is thought that they are continuously produced by steady state collisions between parent bodies in debris disks. How-

TABLE 4

SERKOWSKI LAW PARAMETERS

Star	P_{max} [%]	λ_{max} [μm]	K	χ^2	P_{max} [%] (K =1.15)	λ_{max} [μm] (K =1.15)	χ^2
HD 105	0.10±0.02	0.53±0.05	6±5	18.0	0.11±0.01	0.32±0.03	23.2
HD 10008	0.05±0.01	0.6±0.4	0±3	11.8	0.051±0.004	0.6±0.1	7.4
HD 22049	0.055±0.004	0.60±0.08	1±2	0.03	0.0546±0.0003	0.601±0.009	0.01
HD 31392	25	3.9	1.6	–	404±6034	9±23	317
HD 92945	0.087±0.005	0.5±0.1	1±1	2.8	0.089±0.003	0.58±0.04	1.6
HD 105912	4±70	9±144	0±2	0.5	0.7±0.2	1.7±0.2	0.3
HD 109085	0.057±0.006	0.65±0.04	8±4	3.4	0.049±0.007	0.7±0.3	9.1
HD 197481	0±10	10±216	0±3	2.9	0.10±0.02	1.5±0.2	1.6
HD 217792	730±156223	0±1	1±19	27.5	55±243	0.04±0.03	14.3
HD 121504 B	2.095±0.009	0.576±0.004	1.46±0.08	1.7	2.06±0.02	0.568±0.009	13.0

ever, the levels of warm dust observed in some systems make it unlikely to produce this type of dust in situ. This has re-motivated the debate on the possible origin of the small and hot dust grains in debris disks.

The small amounts of polarization measured in this work are at the limit of our instruments capabilities. In order to efficiently detect smaller polarizations from debris disks, the use of other techniques would be required, such as coronagraphic imaging, capable of suppressing the higher levels of unpolarized radiation from the star, which may hide the small fraction of polarized radiation from the disk. High resolution coronagraphic imaging can be combined with polarimetry to obtain polarization maps of debris disks with evidence of small dust grains. With this combination it is possible to estimate the location of the dust, and to help decide whether the systems identified in this work contain a population of warm dust particles.

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