Astron. Astrophys. 337, 808–814 (1998)

ASTRONOMY
AND
ASTROPHYSICS

An attempt to detect the dust disk of Vega by photopolarimetry, and constraints on the grain size[⋆,⋆⋆]

N. Mauron[1] **and H. Dole**[2]

[1] Equipe d'Astrophysique CC 72, ISTEEM-CNRS-UM2, Place Bataillon, F-34095 Montpellier Cedex 05, France (mauron@merlin.graal.univ-montp2.fr)
[2] Institut d'Astrophysique Spatiale, CNRS & Université de Paris-Sud, Batiment 121, F-91405 Orsay Cedex, France (dole@ias.fr)

Received 22 December 1997 / Accepted 12 June 1998

Abstract. We report on a first attempt to detect Vega's disk through optical scattered light by using linear photopolarimetry. Polarization measurements on the aureole of Vega were carried out between 7″ and 30″ from the star with a 10″ diameter hole and down to polarization level of $\sim 10^{-4}$. No signal reliably attributable to circumstellar dust was detected, and an upper limit to the polarized surface brightness of the disk is derived. This upper limit for Vega's disk is about 200 times lower than the polarized brightness observed around β Pic, at an angular offset of 15″ from the stars.

The upper limit is also compared to a simple model, in which one assumes a plausible total dust mass of $2\ 10^{-8}\,M_{\odot}$, and a pole-on oriented disk with a typical radius of ∼20″ as favoured by far-infrared and submillimetric experiments. We also suppose that the grains are spherical (Mie) particles. Our analysis can exclude that a major part of dust mass would consist of grains of 0.01-0.3 μm, as in the interstellar medium. If a single size is assumed, the observational upper limit favours radii of at least 5-10 μm or larger. If a size distribution including large particles ($\sim 300\,\mu$m) is assumed, the data suggests that only a very small fraction (∼ 1/1000) of the dust mass is in 0.01-0.3 μm grains.

Key words: polarization – circumstellar matter – stars: individual: Vega

1. Introduction

Following the discovery by Auman et al. (1984) of a strong infrared excess emitted by Vega, seen with IRAS and interpreted as being due to a circumstellar disk, considerable efforts have been made to better understand these objects and particularly to characterize their dust. The spatial distribution of the particles, their size or more precisely the size spectrum, are key parameters involved in our understanding of planet formation by dust accretion, or inversely of dust replenishment of the disks by vaporization or collision of small bodies (see for example reviews in Backman & Paresce 1993; Artymowicz 1996, 1997a).

Concerning Vega's dust disk, Auman et al. (1984) had initially proposed grains of more than a millimeter in radius, but later experiments and studies, which envisaged dust replenishment, have favoured smaller grains (e.g. Harper et al. 1984). Van der Bliek et al. (1994) reanalysed the IRAS observations and showed that a significant fraction of the emitting material consists of grains with radii a between 0.1 μm and 10 μm. They concluded that the existence of larger grains is not ruled out, but that their presence is not necessary to explain the IRAS data. A similar grain radius estimate is given by Habing et al. (1996) who presented ISO observations made at $25\,\mu\mathrm{m} < \lambda < 180\,\mu$m and found that dust with $a \sim 3\,\mu$m can fit the infrared photometry. However, these small particles cannot fully account for the submillimetric data, and Zuckerman & Becklin (1993) argued that particles with $a \sim$ 100-300 μm, or even larger, are also present with a minimum total dust mass of $\sim 2\ 10^{-8}\,M_{\odot}$, or half the Moon mass.

The bulk of the mass of these disks probably reside in large grains, but observations of scattered light in the optical domain, which probe the low-size tail of the distribution, are invaluable since they provide information at high angular resolution. However, very few disks have been optically detected up to now, despite extensive and sophisticated surveys (Smith et al. 1992, Kalas & Jewitt 1996). Only the disks around β Pic (Smith & Terrile 1984; Kalas & Jewitt 1995 and ref. therein) and around BD +31° 643 (Kalas & Jewitt 1997) have been imaged. Although coronagraphic masking or other techniques like antiblooming CCD cameras (Lecavelier des Etangs et al. 1993) have been used, the dominant limitation of these experiments remains the intense atmospheric and telescopic halo. It is not straightforward to detect a faint surface brightness above this strong background, which in addition is temporally variable and quite difficult to be modelled and substracted (e.g. Walker et al. 1994, Kalas & Jewitt 1996).

The goal of this work is to explore the possibility of optically detecting disks through their linear polarization. We were

---

Send offprint requests to: N. Mauron

[⋆] Based on observations made at the 2-m telescope of Pic-du-Midi, operated by Observatoire Midi Pyrénées (Centre National de la Recherche Scientifique & Université Paul Sabatier de Toulouse, France)

[⋆⋆] The appendix is only available in the electronical form of this paper guided and encouraged to do so by several qualitative and quantitative considerations. First, the disk of β Pic is strongly polarized, $p = 17 \pm 3\,\%$ in R band over all its extent (Gledhill et al. 1991).

Secondly, stellar haloes are not polarized if the star is not. So they constitute a signal, say I, above which classical techniques of photopolarimetry should be able, in principle, to detect a faint polarized component of the order $pI = 10^{-4}\ I$. This is 10 magnitudes fainter than the halo itself, which seems promising provided the disks are supposed to be somewhat polarized. To illustrate this point, consider the disk of β Pic in blue light. The star's magnitude is B=4.0 . Adopting the profile of a star image as given by King (1971), the halo surface brightness is about 17.0 B-mag arcsec^{-2} at 12$''$ from the star. At this angular offset, the surface brightness of the β Pic disk is 19.2 B-mag arcsec^{-2} (from the data Paresce and Burrows 1987), and with $p = 17\,\%$, one finds a polarized surface brightness of 21.1 B-mag arcsec^{-2}. Therefore, the *apparent* degree of polarization at 12$''$ from the star is of order $10^{-0.4(21.1-17)} = 2.2\,\%$, which is huge compared to feasible accuracy of polarization measurements (0.01 %).

We had also acquired some experience in measuring polarized scattering by circumstellar grains around bright red supergiants such as α Ori and μ Cep (Le Borgne et al. 1986, Le Borgne & Mauron 1989). Therefore, we wanted to test this method to Vega-type disks, and to push photopolarimetric mapping to its limits. Vega was an ideal candidate to do so, in view of its high visible flux, its high elevation in the northern sky, and its interest.

In the following, Sect. 2 contains a short description of the instrumentation. In Sect. 3, we give details about the experimental procedure and difficulties. In Sect. 4, the observational results are presented: the disk was not detected but an upper limit on its linearly polarized brightness has been derived. This result is discussed in Sect. 5. Our conclusions are in Sect. 6, and a few suggestions are finally given.

2. Instrumentation

The observations were carried out with the 2-m telescope of Pic-du-Midi Observatory (Haute-Pyrénées, France), during two runs in July 1995 and August 1996. We used the photopolarimeter *Sterenn* at the Cassegrain focus (f/25). This instrument is fully documented in Le Borgne (1987), and we only give here the main and relevant characteristics.

In the direction of propagating light, there is first a flat mirror which is tilted by 45° and centrally drilled in order to provide a 10$''$ diameter hole. This mirror is the field diaphragm and is convenient for positioning and guiding the star on or off the hole with a small CCD camera and a TV monitor. The mirror is followed by a filter wheel offering: i/ a Johnson B filter used for off-star positions or faint stars; ii/ an identical B filter associated with a neutral density filter d=3.43± 0.06, to be used for Vega itself (the density was calibrated by observing HD 171485 which has B=7.77); iii/ a 100 Å wide filter centered at 4200 Å , used for bright polarization standard stars.

The filter is followed by a half-wave rotating plate, a Wollaston prism which angularly separates polarized light into two beams, and two photomultipliers (PM) which measure simultaneously both linear components, detected as signal modulations. This double-beam configuration is the key for measuring very small polarizations, since it is not sensitive to atmospheric scintillation. The PMs can be fed with four different voltages: these voltages are scaled with ratios 0.29, 0.55, 1.00 and 1.80, which were checked on stars. In addition, there is a shutter in the beam, and the PMs are automatically switched off if saturated. The half-wave plate rotates at 18 Hz, and the PM outputs are analysed with digital synchronous signal processing.

Each measurement, lasting about 7 minutes, comprises a sequence of twenty on-source integrations, preceded and followed by six integrations for dark current and noise measurement. In real time or in subsequent reductions, it is possible to monitor the Q, U and I values from every integration and their standard deviations, together with the evolving values of p and θ resulting from all previous integrations of the sequence. It is quite easy to discard integrations perturbed by cosmic rays, to detect intensity drifts and PM automatic switch-offs, due to bad guiding or strong turbulence. At the end, several measurements are merged for improving the final estimate of Q/I and U/I. This merging has been done only on similar measurements, i.e. sequences were merged when they displayed statistically comparable values of Q/I, U/I and similar intensities (intensities within a factor of 2 for off-star positions). This merging was done with a $1/\sigma^2$ weighting, where σ is the error on Q/I and U/I for a given sequence.

The reliability of *Sterenn* is supported by numerous results obtained in the last fifteen years, for instance the survey of polarization of 1000 stars of the solar neighbourhood (Leroy 1993a,1993b), studies of magnetic fields in Ap stars (Leroy 1995), or maps of circumstellar scattering (Le Borgne et al. 1986, Mauron & Le Borgne 1986, Le Borgne & Mauron 1989).

3. Observing method and difficulties

A critical aspect of our experiments is that we make *off-star* measurements: the 10$''$ diameter aperture is centered at 7-30$''$ from Vega, at north (N), east (E), south (S) or west (W) of the star. The diffraction spikes are oriented NE-SW and NW-SE, and are avoided. Unfortunately, this configuration naturally carries some asymmetry for a number of reasons. The hole is not illuminated homogeneously as for on-star observations, due to the steep gradient of the telescopic stellar image. It is also not the same to measure off-star north and south of the star since for example the star will impact the tilted mirror above or below the central hole. In addition, the hole and the hugely illuminated mirror are necessarily not "perfect", regarding their circular shape and reflectivity, respectively. All this suggests that some intrumental polarization may appear in the off-star configuration, and indeed it does, with significant levels, up to $p = 10^{-3}$ in the worst case as we shall see below.

In order to assess this effect, which we call edge-effect, a first test was carried out on stars other than Vega, and it was done as much as possible on α Peg (B=2.45) and on α Aql (B=1.00). Ideally, it would have been necessary to make a complete map of the edge-effect, that is with offsets from $6''$ to $30''$, and on the four N-S-E-W orientations. But this was not possible by lack of time on one hand, and lack of photons on the other hand. Indeed, for the edge effect to show up clearly, we had to put the hole very near α Peg, i.e. significantly nearer than was done for Vega.

The edge effect was also expected for Vega, and it is in fact one of the main limitations. In order to attempt to disentangle this effect from possible genuine circumstellar polarization, *we rotated the photopolarimeter by 90° around the telescope axis* after a few nights of observations. This was done for both 1995 and 1996 observing runs, and we could carry out numerous measurements in both configurations. So, a second test was that any real circumstellar polarization should show up consistently with both rotation configurations.

4. Observational results

The experimental results are presented in terms of usual diagrams showing Q/I *versus* U/I, where these quantities have been calibrated on standard stars. The central circle always indicates the locus with $p = 2\ 10^{-4}$. The error bars are everywhere $\pm 2\sigma$, except for off-star measurements around α Peg and α Aql for which $\pm\sigma$ is drawn for clarity. In these diagrams, any celestial object (stellar or nebular) with a given polarization must be at the same place, whatever the configuration " before or after rotation" is.

Fig. 1 shows together the weighted average of null polarization standards on one hand, and of Vega itself on the other hand. There is no significant instrumental polarization, taking into account uncertainties. Vega's points marginally suggest a central symmetry linked to rotation, but this symmetry is opposite in 1995 and 1996, even though the instrumentation was strictly identical. It is also not confirmed in 1995 by the $p = 0$ standards. We conclude first that there is no intrumental polarization larger than 10^{-4} *in the "onstar" configuration*. Secondly, Vega itself appears unpolarized ($p < 10^{-4}$), in agreement with previous data (cf. the catalog of Leroy 1993; Vega is HD172167)

Fig. 2 displays all the off-star data points (i.e. averages of measurements as explained above). Big symbols are for Vega, and small symbols for α Peg and α Aql. A label such as "N8,11" refers to a measurement made $8''$ north of the star, and for which the flux received within the $10''$ aperture was found to be $11.\ 10^{-4}$ times that of the star. This relative flux, called I_{rel}, is found to strongly depend on the seeing quality (by factors 3-10), but to a first approximation it is indicative of the proximity of the hole to the star.

For clarity of the text, we explain below only the main implications of Fig.2 , and a few additional comments can be found in Appendix. Fig. 2 shows that:

- About half of the points around Vega, and the one near α Aql, are within the $p = 2.\ 10^{-4}$ circle. This indicates no detectable polarization of the aureole.

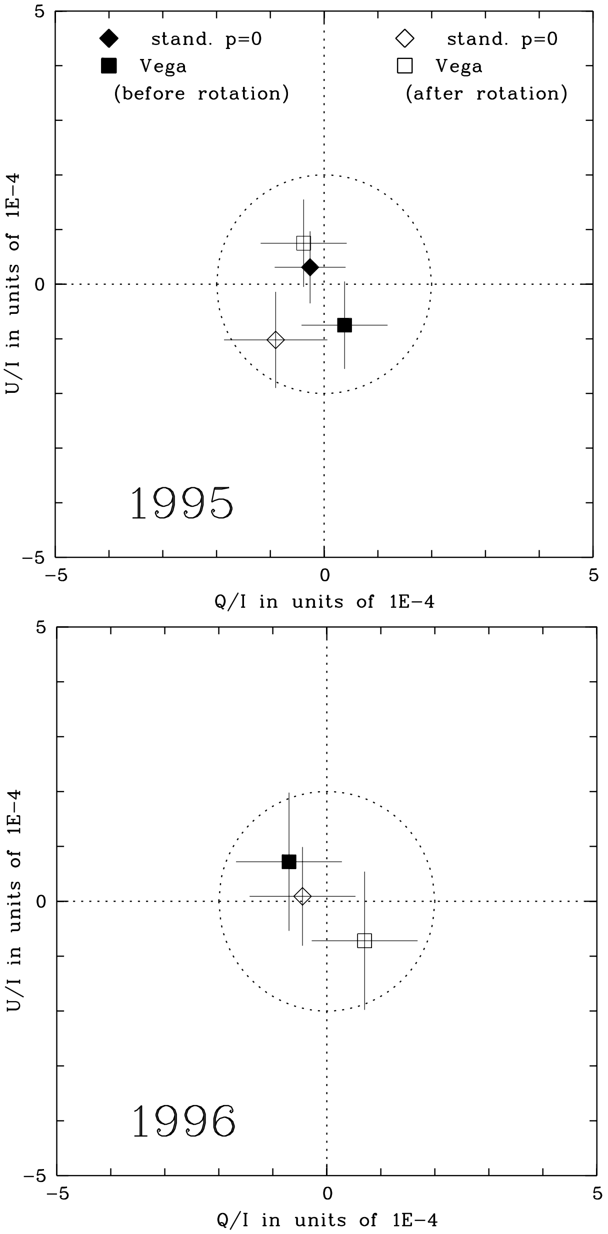

Fig. 1. Polarization measurements of Vega and of standard $p = 0$ stars (on stars). Vega is found to be unpolarized, i.e. $p < 10^{-4}$. Error bars are $\pm 2\sigma$. The circle represents the locus where $p = 2.\ 10^{-4}$.

- There are several measurements around Vega and around α Peg which show significant polarization. The points are scattered near the horizontal axis, with on one hand east and west points in the negative part $Q/I < 0$, and on the other hand north and south points on the positive part $Q/I > 0$. This is exactly the pattern of a tangential (positive) polarization. Because it is best seen in 1995 experiments when the hole was positioned very near the stars, especially very near α Peg, this polarization is attributed to edge effects (instrumental).
- There are a few intriguing points concerning Vega, especially at north and east, which do not display the above pattern. One of them (E22,1.8) show *radial* polarization. Others (e.g. N8,11)

show significant negative or positive values of $U/I > 0$. This indicates tilted polarization vectors (at 45° if Q/I=0). These points are rather peculiar, but again, we attribute them to instrumental effects, because they were never seen and clearly reproduced for both rotation configurations (see appendix for more comments).

In summary, nothing has been detected which could be attributed with certainty to Vega's disk. There is another indirect reason for thinking so. The isophotes of the disk seen in far-infrared by ISO (Heinrichsen et al. 1998) suggests a matter distribution rather circular, without large discrepancy in any direction, to north for instance. The disk pole-on orientation qualitatively agrees with a study of photospheric line profiles by Gulliver et al. (1994) who argues for a rotating star seen pole-on. Consequently, if we assume that Vega's disk is pole-on with good isotropy in its plane (no strong inhomogeneity), the fact that south offsets have never shown any polarized signal (except one, probably due to the edge-effect) is in favour of a non-detection everywhere.

Quantitatively, the observations provide an upper limit to the disk polarized brightness. If the disk polarized brightness had been three times larger than that of the telescopic aureole (which is found to be unpolarized at the level $p \sim 10^{-4}$), it would have been well detected, especially at south where one found little instrumental polarization. This brightness, noted pB/I_*, expressed in arcsec^{-2}, is obtained after dividing $p\,I_{rel}$ by the entrance hole area (78 arcsec^2). This is obtained for a range of θ values, and Fig. 3 shows the result. On this figure, the straight line corresponds to:

$$pB(\theta)/I_* < 5.\,10^{-10}\ (15''/\theta)^2 \quad [\text{arcsec}^{-2}], \qquad (1)$$

with $8'' < \theta < 22''$. This is the final 1σ upper limit for the disk polarized surface brightness.

5. Discussion and comparison with models

We can first compare the above limit to the disk of β Pic. We based our estimation for its brightness in blue on the R-band surface photometry (Kalas & Jewitt 1995), the fact that the scattering is white (Paresce & Burrows 1987), the magnitude of the star (R=3.50), and the assumption that its polarization in B is the same as in R (17%). We find for β Pic:

$$pB(\theta)/I_* = 1.1\ 10^{-7}\ (15''/\theta)^{3.76} \quad [\text{arcsec}^{-2}]. \qquad (2)$$

This shows that at $\sim 15''$ from Vega, our limit is 200 times fainter than that of β Pic. This is consistent with the findings by Kalas & Jewitt (1996). The sensitivity limits established by these authors, based on non-detection through direct imagery, still permits a disk with 0.1 to 0.01 the scattering cross section of β Pic.

One can also compare the obtained limit with a simple model of disk scattering. A small amount of information exists about the quantitative distribution of matter around Vega, essentially because of the lack of high angular resolution observations. Following Habing et al. (1996), all photometric infrared (IRAS, ISO) and submillimeter data can be accounted for with a disk model where *all* grains are at 140 AU from star (θ=18″), with a single dust temperature 84 K, grain size of order 3-10 μm, and absorption efficiency $Q(\lambda)$=const. for $\lambda \sim 20\,\mu$m, and $Q(\lambda) \sim \lambda^{-1}$ for $\lambda \geq 20\,\mu$m. Of course, that does not mean that all the grains reside at 140 AU, but it shows that the radial distribution of matter around 140 AU is rather poorly constrained. Not very different typical dimensions of the disk are derived from analysis of ISOPHOT maps by Heinrichsen et al. (1998).

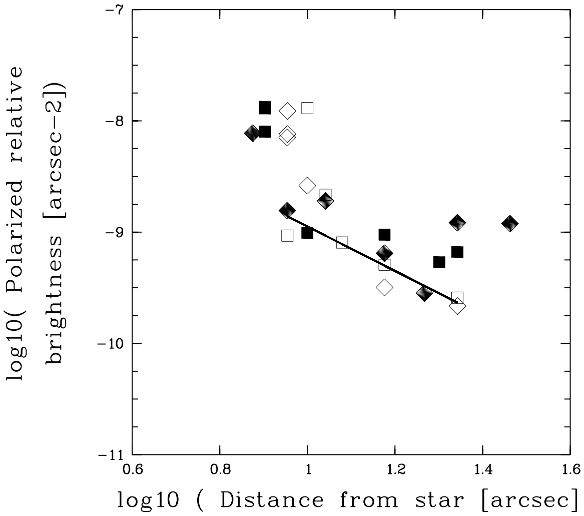

Fig. 3. Measurements of polarized relative surface brightness pB/I_* around Vega, plotted against the distance θ to the star. Symbols are identical to those of Fig. 2. A 1σ upper limit to the disk polarized brightness has been obtained for $8'' < \theta < 22''$, represented by the straight line (see text)

Because the optical brightness of a pole-on disk depends on the surface density of material $\Sigma(r)$ (i.e. $\rho(r)$ integrated along our line of sight), one needs to assume some inner and outer radii. In order to get a plausible estimate of the surface brightness, let us simply adopt r_{in} =100 AU and r_{out} =200 AU, corresponding to 12″ and 24″ at d =8.1 pc respectively. Then, a total dust mass of $\sim 2\ 10^{-8}$ M$_\odot$ implies a mean surface density $\Sigma_{mean} \sim 10^{-6}$ g cm^{-2}. In this hypothesis of a thin homogeneous disk seen pole-on, and assuming spherical dust grains of a single radius a, the disk relative surface brightness B/I_* at angular offset θ (including all polarization) is easily obtained, in sr^{-1}, as:

$$B(\theta)/I_* = \tfrac{3}{4}\ a^{-1}\, Q_{sca}\ \ S(\tfrac{\pi}{2})\ \ \rho_g^{-1}\, \Sigma_{mean}\ \ \theta^{-2}, \qquad (3)$$

where Q_{sca} and $S(\phi)$ are the scattering efficiency and scattering (or phase) function at angle ϕ (with $\int S(\phi) d\omega = 1$), respectively, and ρ_g is the grain density.

Considering first the simplest case of small grains ($a < 0.05\,\mu$m), polarization will be high and positive (i.e. tangential), that is $p \sim$ 50-100 %. The value of Q_{sca} depends on the dust refractive index m: it is 0.1 $(a/0.05\,\mu\text{m})^4$ for $m \approx 1.7 - 0.1\ i$ (astronomical silicates, Draine 1985), and

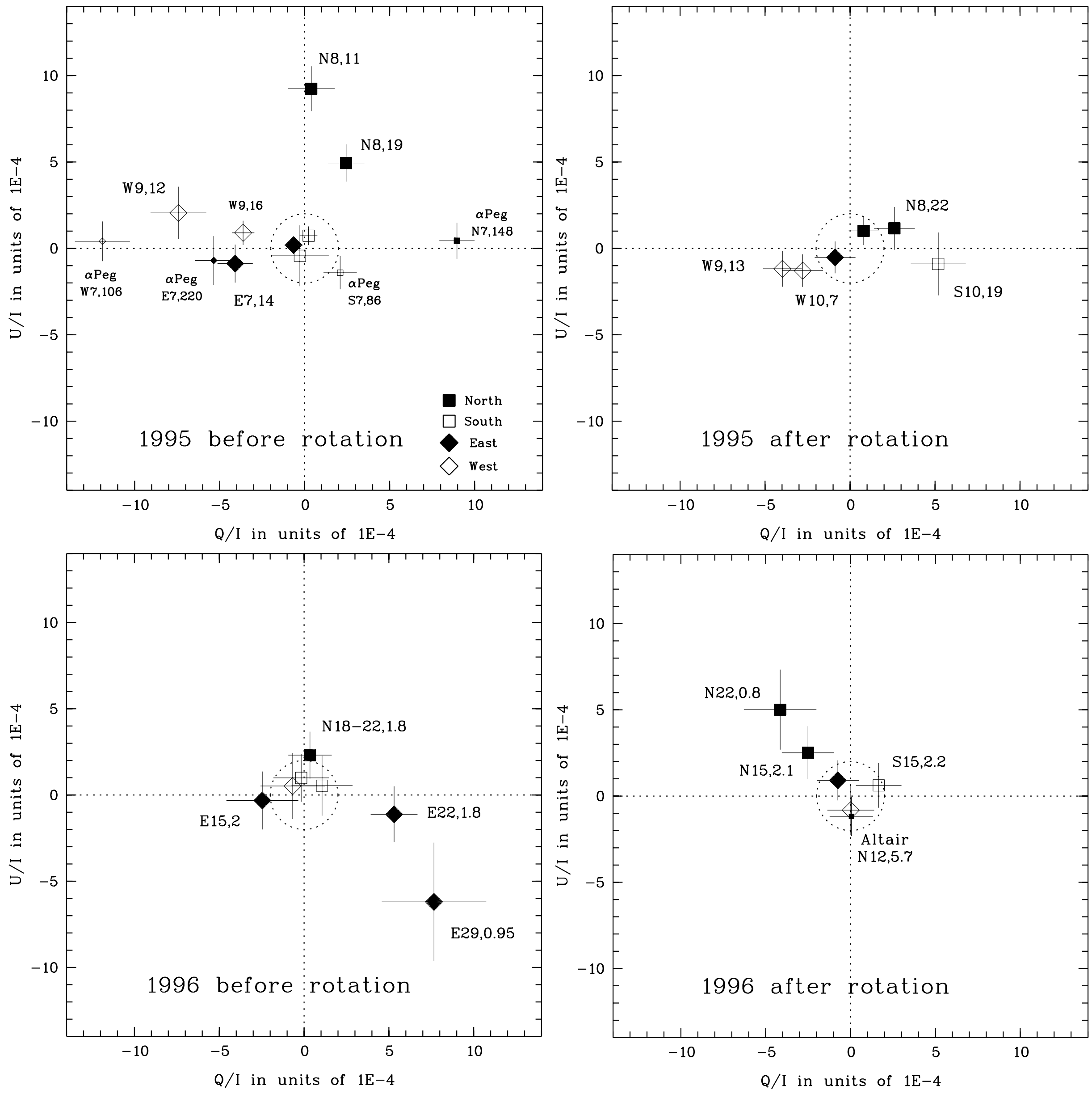

Fig. 2. Polarization measurements of the aureole around Vega. The four panels show separately the data obtained during the 1995 & 1996 runs, and each run was made with two instrumental configurations (i.e. the instrument is rotated by 90°). Each point (e.g. W9,12) is labelled with its position (NSEW), distance to star (9″), and the relative aureole flux received in the 10″ diaphragm, in units of 10^{-4} (12). The points inside the $p = 2.\ 10^{-4}$ central circles are: for 1995 left panel S11,17 S9,9 E11,15; 1995 right panel E9,12 N10,6; 1996 left panel S12,6.3 S22,1.7 W22,1.7; 1996 right panel E15-22,1.9 and W15,2.5 . All the points showing some polarization, and lying outside the $p = 2.\ 10^{-4}$ circles, are interpreted as being due to instrumental effects. No signal from Vega's disk has been detected with certainty (see text).

$\sim$5 times lower for $m \approx 1.2$ (interstellar grains of reflection nebulae, see for example Warren-Smith 1983). In the Rayleigh regime, the phase function at right angle is $S(\frac{\pi}{2}) = \frac{3}{16\pi}$. Finally the grain density ρ_g may be 1 to 2 g cm^{-3}. Taking mid-range values of the above parameters, we find:

$$pB(\theta)/I_{*}=10^{-6}\ (a/0.05\,\mu\mathrm{m})^3\ \ (\theta/15")^{-2} \quad [\mathrm{arcsec}^{-2}]. \quad (4)$$

This is as much as $\sim$2000 times stronger than our observed upper limit expressed in relation (1)! Even taking into account uncertainties on the disk mass and geometry, this limit immediatly indicates that a major fraction of dust cannot be made of such small (0.05 μm) grains.

If one now considers larger grain sizes, one can expect significant changes of each factor of $p\,a^{-1}\,Q_{sca}\,S(\frac{\pi}{2})$. One predicts a maximum of Q_{sca} around unity, and a significant decrease of $S(\frac{\pi}{2})$ due to strong forward scattering by large grains, and of course a decrease of a^{-1}. Calculations of pB/I_{*} were carried out by Mauron & Le Borgne (1986) and Le Borgne & Mauron (1989), for the case of a spherical r^{-2} number density distribution of dirty silicates grains. Although with our assumption of a pole-on thin disk, the scattering angle is ~90° for all grains, which is not the case for a r^{-2} spherical envelope, we believe that there are enough uncertainties concerning the real distribution of matter around Vega that we may rely on their results to derive reasonable conclusions and order of magnitude estimates of pB/I_*. Taking the case $a = 0.05\,\mu$m as reference value for pB/I_*, Fig. 1 of Mauron & Le Borgne (1986) shows that pB/I_* still increases by a factor $\sim$5 and is maximum for a size $a \sim 0.1\,\mu$m. There is a subsequent decrease with negative polarization for $a \sim 0.16$-$0.5\,\mu$m. Finally beyond 0.5-1 μm, positive p reappears, but smaller and smaller values of pB/I_* are expected, with $pB/I_* \propto a^{-1}$. We find that if a=5 μm or 50 μm, pB/I_* is expected to be 50 times larger, or 5 times larger than our 1σ upper limit, respectively. Equality is reached for a=250 μm. Therefore, if we assume single-sized grains obeying Mie scattering, the data favour very large grains. Because there are uncertainties on the disk characteristics (perhaps, we have overestimated Σ_{mean} by a factor ~10), we find that a is at least 5-10 μm.

However, the picture of single-sized spherical particles is of course very crude. Let us adopt a size distribution such as a$^{-3.5}$. This type of distribution has been envisaged for the disk of β Pic (Artymowicz 1997a). We assume that there are small and large grains with a being between a_{min} ($a_{min} \leq 0.05\,\mu$m) and a_{max}, with a_{max} considered as a parameter. Then, most of the mass is in large grains: the fraction $f(a)$ of mass in grains with radii less than a is equal to $(a/a_{max})^{0.5}$. For example, if a_{max} = 300 μm, $f(a = 0.3\,\mu m)$ is $(0.3/300)^{0.5} \approx 3$ % only. But most of the polarized signal is due to small grains around $\sim 0.1\,\mu$m. When a_{max} is increased, starting from $\sim 0.3\,\mu$m, the resulting polarized signal decreases approximatively as ${a_{max}}^{-0.5}$, as shown for example in Fig. 4 of Mauron & Le Borgne (1986). We find that if a_{max} is set to 0.3, 10, or 300 μm, the values of pB/I_* are expected to be 1800, 300, 60 times larger than the observed 1σ upper limit, respectively. This shows that there are probably much fewer polarizing grains ($a < 0.3\,\mu$m) than implied by the $a^{-3.5}$ distribution assumed above, if a_{max} is equal to 10 μm or even 300 μm. In other words, only a very small fraction ($\sim$ 1/1000) of the total dust mass can be put in grains with $a < 0.3\,\mu$m, otherwise the disk would have been detected. This result is consistent with the fact that small grains, if produced in the disk, are very efficiently removed because of vaporization, or because their radiation pressure to gravity ratio β is large (typical values of β in the disk of Vega are about 100 for $a \leq 0.1\,\mu$m, and decrease to $\sim$1 for a = 5-10 μm, if an interstellar composition is assumed; Artymowicz 1997b).

Finally, it is prudent to note that, above, we have ignored a number of more or less known grain properties which are also relevant for polarization and scattering, i.e. the complex refractive index, aspherical shapes, roughness and porosity, etc. For example, Fig. 8 of Le Borgne & Mauron (1989) shows that the amount of polarized scattered light by silicate spheres of radii larger than $\sim 0.3\,\mu$m depends strongly on the imaginary part of the refraction index, and pB/I_* may be significantly lower than mentioned above. Perrin & Sivan (1991) also report important effects of roughness and porosity, which cannot be ignored as soon as the grain diameter is comparable to wavelength (about scattering effects by aspherical shapes, see also the works of Wolff et al. 1994, Kolokolova et al. 1997). So, using models more sophisticated than Mie theory are certainly desirable for a rigourous comparison with our limit, especially when considering scattering by grains of several microns. Nethertheless, the results of our analysis, which favours large grains and a tiny fraction of small grains (if any), are in good agreement with indications based on infrared and submillimetric data.

6. Conclusions and suggestions

The main conclusions of this work are:

1. For the first time, a sensitive optical photopolarimetric mapping around Vega has been presented. This experiment was carried out with the hope of detecting its circumstellar matter, or at least to explore the difficulties of such a technique which might be applied to other objects. The disk of Vega has not been detected, but an upper limit to its linearly polarized surface brightness in the B band has been derived. This limit is ~200 times fainter than the polarized brightness of the disk of β Pic.

2. This upper limit implies that the grains cannot be similar to those of diffuse interstellar matter, with radii between 0.01 μm and 0.3 μm. The fraction of the total dust mass corresponding to such small grains has to be very small, of order $\leq$ 1/1000. Taking into account uncertainties concerning the disk dust mass and geometry, the data are also qualitatively consistent with grains of 5-10 μm or/and larger, in agreement with previous works based on far-infrared or submillimeter observations.

3. On the experimental front line, the main limitation we met seems to be some instrumental polarization arising from the uncommon use of the photopolarimeter, since its 10$''$ entrance hole has to be positioned a few arcsec off the bright star, and is consequently not homogeneously illuminated. This "edge effect" was first found to yield mostly tangential or null polarization, but we also experienced a few surprising and robust measurements showing polarization vectors which are radial or tilted by 45°. An optimistic observer could believe them, at first sight, to be attributable to some circumstellar contribution. The adopted remedy against these effects was to rotate the photopolarimeter, and demanding that any presumably circumstellar pattern be found on both configurations: none was found, unfortunately.

Our instrumentation was certainly not optimized for the project, and future observations on Vega or Vega-type systems may benefit from the following suggestions: a larger collecting area such as with the 10m Keck telescopes, and perhaps a larger bandwidth (B+V) would provide ~ 50 times more photons per arcsec^2 than with our apparatus. This would allow a faster and more extended mapping, with especially better accuracy and/or better angular resolution. Using a drilled tilted mirror as entrance diaphragm may not be the best at all, and could be avoided if accurate positionning and guiding is offered by the telescope, although this will not eliminate illumination asymmetry. Systematic tests on Sirius or other bright stars should be done. Perhaps the use of a red or near infrared band would be more fruitful. Finally, the goal of controlling all factors producing small polarized artefacts at the 10^{-5} to 10^{-4} level should be attempted. This is a challenging aspect of polarimetry, but our opinion is that Vega's disk or other systems deserve the needed efforts, in view of their importance in our knowledge of planet formation.

Acknowledgements. The authors are most grateful to Jean-Louis Leroy, who was responsible for the smooth running of the photopolarimeter, and gave many ideas and generous help. The authors thank also the staff at Pic du Midi for assistance during observations. N.M. especially thanks Mike Jura for many discussions. Constructive comments on the manuscript from Thibaut Le Bertre, Nikolaï Voshchinnikov, Patrick de Laverny and the anonymous referee were greatly appreciated. This work has been partially supported by grants from Pic du Midi Observatory and University of Paris VI (to H.D.), and the Groupes de Recherche of the Centre National de Recherche Scientifique "Physico-chimie du Milieu Insterstellaire" and "Milieux Circumstellaires" (to N.M.).

References

Artymowicz P., 1996, Vega Type Systems. In: Kaufl K.U. & R. Siebenmorgen (eds) " The Role of Dust in the Formation of Stars". Springer, Berlin.

Artymowicz P., 1997a, Annu. Rev. Earth Planet. Sci. 25, 175

Artymowicz P., 1997b, ApJ 490, 863

Aumann H.H., Gillett F.C., Beichman C.A., et al. 1984, ApJ 278, L23

Backman D.E., Paresce F., 1993, in Levy E.H., Lunine J.I. (eds) "Protostars and Planets III.", Univ. of Arizona, Tucson, p. 1253

Draine B.T., 1985, ApJSS 57, 587

Gledhill T.M., Scarrott S.M., Wolstencroft R.D., 1991, MNRAS 252, 50P

Gulliver A.F., Hill G., Adelman S.J., 1994, ApJ 429, L81

Habing H.J., Bouchet P., Dominik C., et al., 1996, A&A 315, L233

Harper D.A., Loewenstein R.F. & Davidson J.A., 1984, ApJ 285, 808

Heinrichsen I., Walker H.J., Klaas U., 1998, MNRAS 293, L78

Kalas P., Jewitt D., 1995, AJ 110, 794

Kalas P., Jewitt D., 1996, AJ 111, 1347

Kalas P., Jewitt D., 1997, Nature 386, 52

King I.R., 1991, PASP 83, 199

Kolokolova L., Jockers K., Chernova G., Kiselev N., 1997, Icarus 126, 351

Le Borgne J.F., 1987, Polarimétrie des enveloppes d'objets astrophysiques évolués et de la comète de Halley, Thèse de Doctorat d'Etat, Université Paul Sabatier, Toulouse, France

Le Borgne J.-F., Mauron N., Leroy J.-L., 1986, A&A 168, 211

Le Borgne J.-F., Mauron N., 1989, A&A 210, 198

Lecavelier des Etangs A., Perrin G., Ferlet R., et al. 1993, A&A 274, 877

Leroy J.-L., 1993a, A&AS, 101, 551

Leroy J.-L., 1993b, A&A 274, 203

Leroy J.-L., 1995, A&AS 114,79

Mauron N., Le Borgne J.-F., 1986, A&A 168, 217

Paresce F., Burrows C., 1987, ApJ 319, L23

Perrin J.-M., Sivan J.-P., 1991, A&A 247, 497

Smith B.A., Fountain J.W., Terrile R.J., 1992, A&A 261, 499

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

Van der Bliek N.S., Prusti T., Waters L.B.F.M., 1994, A&A 285, 229

Walker G.A.H., Walker A.R., Racine R., Fletcher J.M., McClure R.D., 1994, PASP 106, 356

Warren-Smith R.F., 1983, MNRAS 205, 349

Wolff M.J., Clayton G.C., Martin P.G. & Schulte-Ladbeck R.E., 1994, ApJ 423,412

Zuckerman B., Becklin E.E., 1993, ApJ 414, 793

Note added in proof: This work was finished when we learnt the results of Holland et al. (1998, Nature 392, 788). They show a 850μm image of Vega's disk (lobe 14$''$ FWHM). The dust emission map is rather asymmetric, with a blob peaked at 9$''$ to the northeast. We did not observe at this position in order to avoid the diffraction spikes (oriented NE-SW and NW-SE), but it is interesting to note that the polarization measurements which appear very surprising were obtained at north and east of Vega (see Fig. 2 and the text). Clearly, more observations are needed to establish the reality of an optical detection, if it is the case.