Are there Aligned Grains Around Young Stellar Objects?

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Abstract. The light at visible and near-infrared wavelengths from Young Stellar Objects (YSOs) is polarized by scattering by small particles, mostly dust grains. In the denser circumstellar disks there is multiple scattering which is responsible for the observed patterns of aligned polarization vectors. Circular polarization has also been detected in a few YSOs, both integrated over the whole region or spatially resolved. We investigate the interpretation of these observations in the context of models incorporating scattering by grains of ellipsoidal shape. The Fredholm integral equation method and the T-matrix method are used to obtain the elements of the scattering matrix and yield very similar results. We consider the effects of grain rotation and investigate the F_{11} and F_{41} elements which have particular relevance to circular polarization. The results are finally used to compute polarization maps for comparison with observations.

1. Introduction

Linear polarization from T Tauri stars is produced by scattering of stellar light by circumstellar dust grains (Bastien & Landstreet 1979). In many cases, the density in the circumstellar environment is such that multiple scattering is needed to explain the pattern of aligned vectors observed around many Young Stellar Objects (YSOs) (Bastien & Ménard 1988, 1990). Circular polarization observations of YSOs showed low polarization levels, typically $< 1\%$, compatible with multiple scattering on spherical grains. A significant development occured when a large (≈ 17 %) circular polarization was detected in OMC-1 in the K-band (Chrysostomou et al. 2000), requiring a significant change in the models. Additional recent observations are reported by Clayton et al. (2004).

Submm polarimetry of YSOs demonstrate clearly that aligned nonspherical grains are needed, at least far from the star (see the review by Tamura 2004), but what can we say about aligned grains from optical and near-infrared observations? Although there is a zone which is field-free near the star (typically 0.25 $\approx< r \approx<$ 6 AU, depending on the density distribution) (Matsumura & Pudritz 2003), it is rather small and the possibility of finding aligned grains relatively close to the star still exists. This is what we want to explore in more details.

The Fredholm integral equation method (Holt, Uzunoglu, & Evans 1978; Matsumura & Seki 1991, 1996a,b) and the T-matrix method (Mishchenko 2000; Mishchenko et al. 2000) have been used for our calculations. A comparison of the dependence of circular polarization, the ratio F_{41}/F_{11} of the elements of the scattering matrix, on the size parameter x for both methods produced an agreement to better than 10^{-4} (Matsumura & Bastien 2004; hereafter MB).

2. Results and Discussion

To investigate the effects of aligned grains, we considered the scattering problem when the alignment is not perfect. We assume that the symmetry axis of the grain precesses around the direction of the magnetic field at a constant precession angle θ_A. This is related to the Rayleigh reduction factor as $R = (3\cos^2\theta_A - 1)/2$. For oblate grains (the case we are considering here), R goes from 0 to 1. R represents a measure of the degree of alignment.

We made calculations for oblate grains with axial ratio 1.5 for amorphous carbon (BE) with $m = 2.3088 + 0.7765i$ at $\lambda = 0.80$ μm. Equivalent results for silicates are given by MB. We used a size distribution from 0.08 to 0.28 μm with a power law of index -3.5. The results for the phase function as a function of the scattering angle are presented in Figure 1, for the linear and circular polarizations in Figures 2 and 3 respectively.

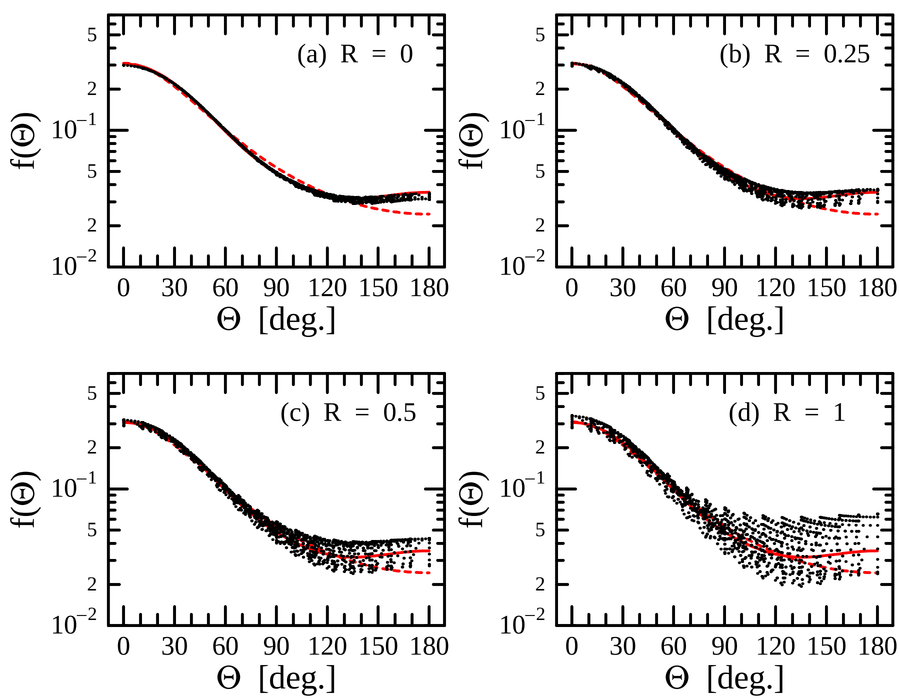

Figure 1. Phase function for amorphous carbon (BE). The alignment goes from no alignment ($R = 0$) to perfect alignment ($R = 1$). Dots show the results for oblate grains and solid lines for spherical grains of the same volume. The best fit Henyey-Greenstein function is shown by the dashed lines.

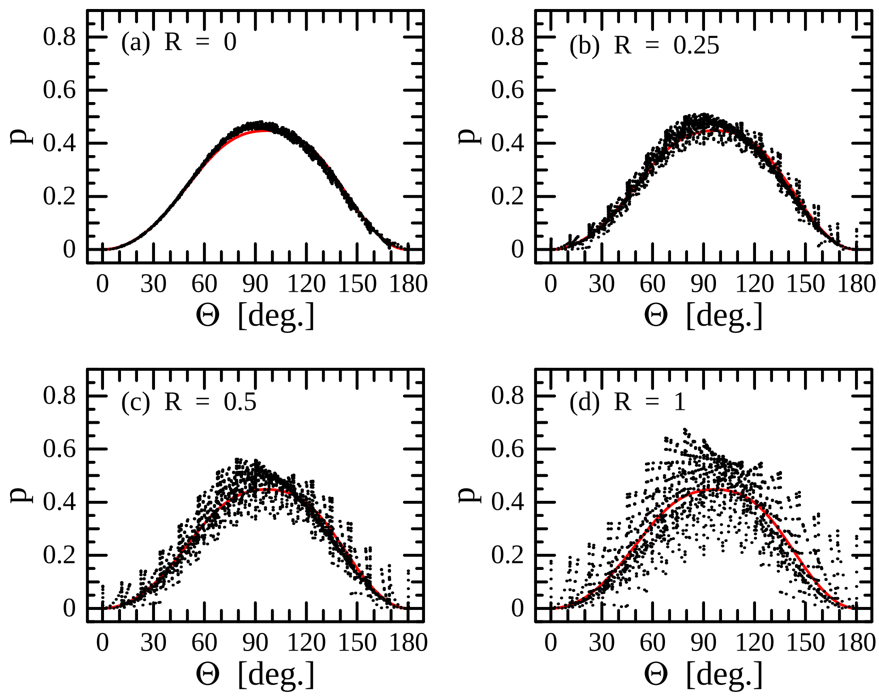

Figure 2. As in Figure 1, for the degree of linear polarization. The lines show the results for spheres.

The scattering angle depends on three other angles: the direction of incident light with a polar angle θ_i, the direction of scattered light with polar θ_s and azimuthal ϕ_s angles. We change each angle in steps of 11.5^o, so that 2601 cases are estimated. The figures show a strong dependence on the Rayleigh factor. When there is no alignment ($R = 0$), the dependence follows approximately that of a sphere with the same volume. As the alignment improves, the spread around the spherical solutions increases. The linear polarization for $R = 0$ is approximately the same as that of the equivalent sphere (Fig. 2). However, for silicate grains it is significantly underestimated by spheres (see Fig. 3 in MB). The circular polarization can reach absolute values up to 20 % (see Fig. 3).

To illustrate the results obtained so far, we computed maps of the scattering by perfectly aligned grains for various inclinations, assuming a flared disk with an opening (polar) angle of 60^o. In Figures 4 and 5 we present those for an inclination of 90^o. The difference in circular polarization between the two different grain compositions is quite obvious.

To summarize, scattering by poorly aligned grains produce results similar to those for spherical grains, but scattering by well aligned grains yield significantly different results. The sign of the circular polarization depends on the scattering geometry, the grain size, the wavelength and the grain material. Silicates and amorphous carbon differ in sign for $x \approx 2-4$, and also with a size distribution.

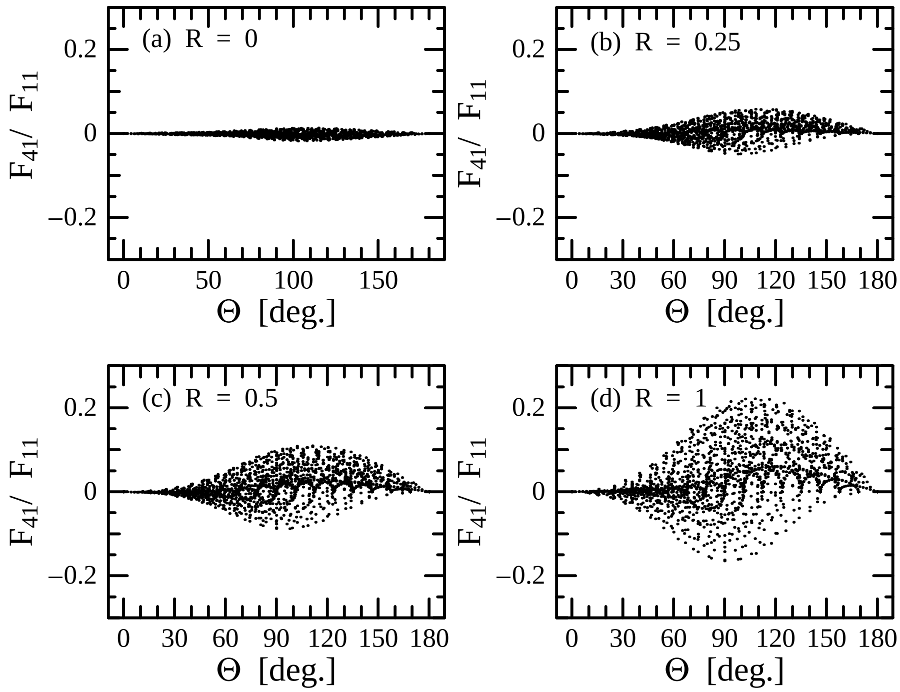

Figure 3. As in Figure 1, for circular polarization.

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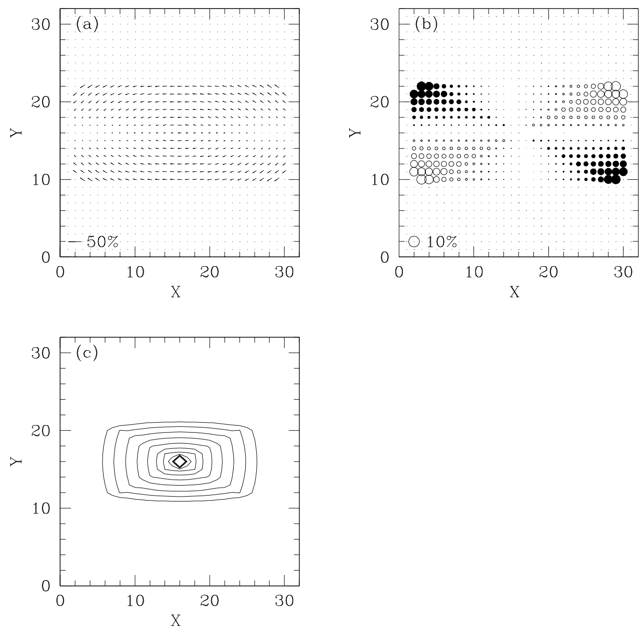

Figure 4. Maps for silicate ellipsoidal grains for an inclination of 90^o. (a) Linear polarization with the scale as indicated. (b) Circular polarization, open circles representing positive circular polarization. (c) Intensity contours.

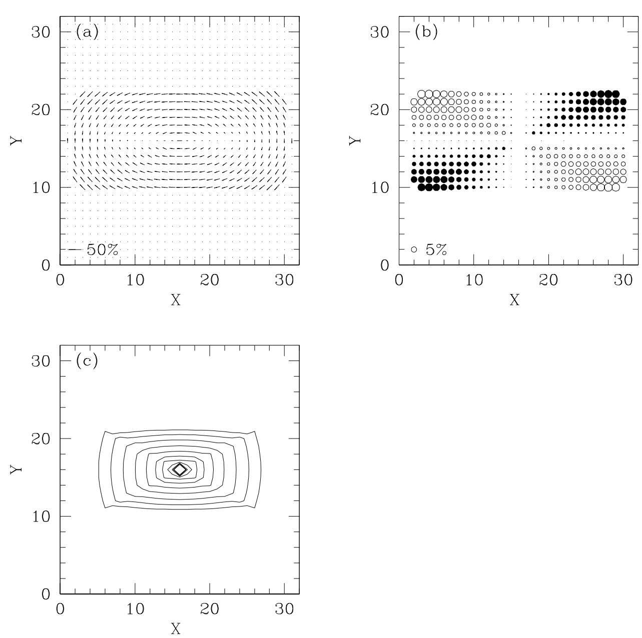

Figure 5. Same as in the previous figure, but for amorphous carbon. Note the different signs in these two circular polarization maps.