Near-infrared polarization in the central parsec of the galactic center

Rainer M Buchholz¹, Gunther Witzel¹, Rainer Schödel², Andreas Eckart¹,³, Markus Bremer¹, and Koraljka Muzic⁴

¹ I. Physikalisches Institut der Universität zu Köln, Zülpicher Strasse 77, 50937 Köln, Germany
² Instituto de Astrofísica de Andalucía (CSIC), Glorieta de Astronomía s/n, E-18008 Granada, Spain
³ Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
⁴ University of Toronto, Department of Astronomy and Astrophysics, 50 St. George Street, Toronto, ON M5S 3H4

E-mail: buchholz@phi.uni-koeln.de

Abstract. The GC offers unique opportunities to study stellar and bow-shock polarization effects in a dusty environment. NIR polarimetry of the stellar and bow-shock sources in the central parsec is presented for the first time at NACO resolution (AO assisted, ESO VLT). We present polarization maps of the central 3”x19” and spatially resolved polarimetry of the known extended bow-shock sources in this region. The measured foreground polarization is largely parallel to the Galactic plane, with average values of 5.5% at 15° (Ks-band) and 9.5% at 20° (H-band) in the center of the FOV. These values vary over the field-of-view, and we suggest that this may be caused by local dichroic extinction on dust grains in the Northern Arm of the Minispiral. It was possible to isolate the intrinsic polarization of the two bow-shock sources contained in the sample, IRS 21 and 1W, and both show similar intrinsic polarization degrees of 5.5% respectively 7.8% (Ks) and 6.9% (H, only 1W) at polarization angles coincident with previous MIR findings, both in total and spatially resolved. The spatial polarization pattern of both sources hints at the processes likely responsible for the intrinsic polarization: scattering on and emission from elongated, aligned grains.

1. Introduction
The Galactic Center, located at a distance of ~8 kpc (see e.g. [4]), contains the densest star cluster in the galaxy. Shrouded by more than 30 mag of optical and still ~3 mag of Ks-band extinction [11], it provides the opportunity to study the relation between extinction and polarization. The foreground polarization towards the GC has been measured previously as 4% at 25° at 0.5-1.0” resolution [3, 7]. The data presented here examines this region at much higher resolution and greater depth than ever before, enabling polarization measurements on an unprecedented number of sources in this region, including resolved polarimetry on two known bow-shock sources (IRS 1W and IRS 21, see [12]).

2. Observation and data reduction
The data used here were obtained with the NACO adaptive-optics assisted instrument at the ESO VLT UT4 on Paranal, Chile (programs 073.B-0084(A), H-band, 179.B-0261(A) and 083.B-0031(A), both Ks-band), using a Wollaston prism in conjunction with a half-wave plate. This
yielded four images for each dither position, at 0°, 45°, 90°, and 135°. These images were flat-fielded, sky-subtracted, corrected for dead/hot pixels, and combined to a mosaic for each channel.

We applied a photometric method recently presented by [10] in order to achieve the necessary precision: deconvolution-assisted PSF fitting photometry. This method counters the problems of PSF variation over the field-of-view (FOV) due to anisoplanatism, as well as crowding in a densely populated region like the central parsec. We achieved photometric uncertainties of better than 3% (Ks-band) respectively 6% (H-band) for most sources brighter than 16 mag in the Ks-band. For details on the application of this method, please see [2].

For our study of the two bow-shock sources in the FOV, IRS 1W and IRS 21, we applied a Lucy-Richardson deconvolution with a PSF determined from bright sources in the IRS 1 and IRS 16 cluster, followed by aperture photometry (with overlapping apertures of 27 mas covering regions of significant flux).

To account for the instrumental polarization of NACO, we used the model developed by [13] to calibrate the data. The instrumental polarization sets a lower limit for the systematic uncertainties of the polarization parameters, with $dp = 0.5\%$ and $d\theta = 5^\circ$.

The intrinsic polarization of the bow-shock sources was measured by assuming that the foreground polarization can be treated as a simple linear polarizer, which can then be described by a Müller matrix. When this matrix is inverted and applied to the measured Stokes vector of an intrinsically polarized source, this yields the actual intrinsic polarization parameters of that source. The reliability of this method depends on the accuracy of the assumed foreground polarization. This value is estimated based on neighboring, non-extended sources.
3. Results and discussion

3.1. Ks-band polarization

The polarization parameters of 194 sources brighter than 16 mag were measured in the Ks-band dataset (see Fig. 2a). For fainter sources, the photometric uncertainty, insufficient completeness and source crowding start to become too large to determine the polarization reliably.

The polarization angles in the central arcseconds mostly follow the orientation of the galactic plane within the uncertainty limits (31.4°, see [8], while angles of ~25-30° are found in this work), while they are slightly steeper (~5-15°) towards the eastern edge of the FOV (see Fig. 2a). A small number of sources west of Sgr A* also shows similar steep angles, but there are too few reliable sources there to allow any conclusions.

The distribution of the polarization angles (see Fig. 2c) can be fitted with a single Gaussian, peaked at 20° with a FWHM of 30°. Using the FWHM as a measure for the uncertainty (with $\sigma = \frac{FWHM}{2\sqrt{2\ln(2)}}$), this yields $\theta = 20° \pm 13°$. Using a fitting function with two Gaussian peaks yields a significantly lower $\chi^2$ (by a factor of 3). The two peaks are fitted at $\theta_1 = 10° \pm 4°$ (FWHM of 10°) respectively $\theta_2 = 26° \pm 8°$ (FWHM of 20°). Considering the uncertainties of the polarization angles (up to 15°), it can be questioned if these two peaks are indeed a real feature, with the distance between the peaks of the order of these typical errors.

The polarization degree also appears to vary over the field, with values of 4-5% in the central region and 8-10% towards the eastern edge (and for some western sources, but with the same
Figure 3. H-band polarization in the innermost 3" × 16.5". (a): Polarization map, red lines indicate the polarization (only shown for sources with reliably measured parameters). (b): Polarization degrees, logarithmic plot. The red line indicates a single peak Gaussian fitted to the histogram, while green lines denote two separately fitted Gaussian peaks. The blue line indicates the sum of these two Gaussians. (c): Polarization angles. Lines denote fitted Gaussians as described for (b).

caveat as for the polarization angle). Especially sources in the area around the IRS 1 sources show these higher polarization degrees. The logarithms of the polarization degrees were fitted with a Gaussian (peaked at (5.1 ± 1.7)%, FWHM of 4.0%, see Fig.2b), and just as it was the case for the polarization angles, the fit was quite poor. Repeating the fit with a double Gaussian yielded two peaks at (4.6 ± 0.8)% respectively (7.7 ± 1.2)%, with FWHMs of 1.8% respectively 2.8% and a significantly better $\chi^2$ (by a factor of 8). The relative uncertainties of the polarization degree reach up to 30%, and this limits the confidence in the two fitted peaks. Comparing the two fitted Gaussian distributions for both parameters reveals that a similar number of stars are contained in the 10° and the 7.7% peak (∼25-30%), respectively the 26° and 4.6% peak (∼70-75%). This confirms the general trends found in Fig.2a and indicates that the fitted peaks indeed correspond to a real feature.

3.2. H-band polarization
In the H-band, reliable results could be obtained for 163 sources brighter than 18 mag. The limit of 18 mag corresponds to the limit of 16 mag in the Ks-band, assuming a typical H-Ks of ∼2 mag (with H-Ks_{intrinsic} ∼0 mag and A_{H}-A_{Ks} ∼2 mag, see e.g. [11]). The lower number of sources with reliable polarization compared to the Ks-band can be attributed to the significantly lower Strehl ratio of the H-band data (0.17 compared to 0.27 in the Ks-band). The polarization angles found here are very similar to those in the Ks-band, but with a more uniform distribution.
over the FOV (see Fig.3a). The distribution of the polarization angles can be fitted well with a single Gaussian, peaking at $20^\circ \pm 8^\circ$ (FWHM of $19^\circ$, see Fig.3c). Fitting this distribution with a double Gaussian produces a slightly better $\chi^2$, but this can be expected for increasing the number of fitting parameters. A single Gaussian fits the distribution with sufficient accuracy, compared to the poor fit with a single Gaussian function for the Ks-band polarization angles. Typical errors of the polarization angle reach about $12^\circ$.

The polarization degree also appears to be quite uniform over the FOV, with typical values of 8-12%. Fitting the logarithms of the polarization degrees with a single Gaussian leads to a peak at $(9.8 \pm 0.7)%$ (FWHM of $1.7\%$), satisfyingly matching the data (see Fig.3b). The data was also fitted with two Gaussian peaks for comparison, but as it was the case for the polarization angles, this only improves the fit marginally. The relative uncertainties of the polarization degree are of the order of up to 40%.

3.3. Polarization efficiency

The Ks-band polarization degrees were compared to the extinction map presented by [11]. Fig.4 shows the polarization efficiency $p_{Ks} / A_{Ks}$ plotted against the Ks-band extinction $A_{Ks}$ taken from the extinction map at the location of each source. As it turns out, almost the same distribution of $A_{Ks}$ is found for sources with $p_{Ks} < 6\%$ ($pK^-$) and $p_{Ks} > 6\%$ ($pK^+$), which in turn leads to an offset between the two sub-datasets in polarization efficiency. They are therefore plotted separately in Fig.4. Sources with less than 3% polarization were excluded, since this low value indicates either a foreground source or intrinsic polarization perpendicular to the foreground (e.g. in IRS 1W). In both of these cases, a comparison with an extinction map would not produce meaningful results.

The distributions can be fitted with a power law:

$$\frac{P_{\lambda}}{A_{\lambda}} \propto A_{Ks}^{\beta}$$

yielding power law indices of $\beta_{pK^-} = -0.4 \pm 0.4$ resp. $\beta_{pK^+} = -0.5 \pm 0.7$. Despite the large errors which stem from considerable scatter of the parameters, the $pK^+$ and $pK^-$ values match the relation found by [5], who examined a large number of sources covering a range in optical depth of about a factor of 100. In that study, a power law relation with $\beta \sim -0.25$ was found, and the author proposed a model where the magnetic field along the LOS consists of a constant and a random component, thus leading to different grain alignment in each section along the
Comparing to the pK$^{-}$ values, a significant offset in polarization efficiency is detected for the pK$^{+}$ sources, while the underlying power law appears to be very similar. This might indicate that the additional polarization observed for the pK$^{+}$-sources is caused by a local contribution, likely by dust in the central parsec itself. Even if this additional local dust only contributes an insignificant amount to the total extinction, it can still lead to such a strong influence on the total polarization, since the local dust can be assumed to be aligned efficiently. A similar dust column density along the LOS might also consist of aligned grains, but the random component would be averaged out and leave only a small net contribution. In order to produce such a deviation along the LOS, a very specific and therefore unlikely dust configuration would be required.
3.4. Intrinsically polarized bow-shock sources

IRS 1W shows the characteristic horseshoe-shape of a bow-shock source (see e.g. [12]), in consistence with the relative velocities of the streaming material of the Northern Arm [6] at the location of the source and the proper motion of IRS 1W itself (velocities plotted in Fig.5, see [9]). The total polarization of IRS 1W was measured as $(1.8 \pm 0.5)\%$ at $(−37 \pm 5)°$ East-of-North in the Ks-band. A higher value of $(4.6 \pm 2.5)\%$ at $(−85° \pm 8°)$ is given by [7], but this may be an effect of contamination by neighboring sources due to insufficient resolution. If it is assumed that the foreground polarization for this source is the same as for the surrounding objects and a depolarization matrix with the parameters for $p = 7.6\%, \theta = 9.2°$ is applied, this yields a total intrinsic polarization of $(7.8 \pm 0.5)\%$ at $(−75 \pm 5)°$.

In the H-band, the total polarization of IRS 1W is measured as $(5.2 \pm 0.5)\%$ at $(12 \pm 5)°$ East-of-North. The polarization angle appears typical for a stellar source affected by foreground polarization, but the polarization degree is much lower than the $\sim 12\%$ found for stellar sources in the vicinity. The application of a depolarization matrix with $p = 12\%, \theta = 15°$ leads to an intrinsic polarization of $(6.9 \pm 0.5)\%$ at $(−73 \pm 5)°$.

Fig.5(a and c) shows resolved polarimetry of IRS1W in both wavelength bands. Polarization degrees of about 10-20 % with very similar polarization angles for regions with significant flux are found. Apparently, the polarization degree is lower by a factor of up to $\sim 3$ around the apex compared to the tails (this feature only appears in the Ks-band, while the observed polarization angles and degrees are otherwise very similar in both bands).

IRS 21 is not covered by the 2009, high quality polarimetric dataset, but several data-sets with a rotated FOV are available in the ESO archive that contain this source (the data-set used here has the best Strehl ratio of the available data with this FOV). The total polarization of IRS 21 was measured as $(9.1 \pm 0.2)\%$ at $(16.4° \pm 0.3°)$, which agrees very well with the value given by [7] (IRS 21 is more isolated than IRS 1W, so lower spatial resolution can still provide accurate results). After applying a depolarization matrix with polarization parameters determined from the surrounding point sources (5% at 30°, determined on only two sources close to IRS 21 and thus not as reliable as the values for IRS 1W), IRS 21 appears to have a total intrinsic polarization of $(6.1 \pm 0.5)\%$ at $(5 \pm 5)°$ degrees. Unfortunately no polarimetric H-band data covering IRS 21 are available.
Fig. 6a shows the Ks-band polarization of individual regions. Polarization degrees of about 3-8% are measured here, with less uniform polarization angles than those found for IRS 1W in regions with significant flux. In addition, rather an increase than a decrease of the polarization degree is detected towards the apex.

The intrinsic polarization degree found for this source is slightly lower than that of IRS 1W, while both sources have very different intrinsic polarization angles. This can be explained by the relative motion of both sources to the ambient material and the local magnetic fields (see [9] for the proper motions of both sources, the streaming motion in the Northern Arm was taken from [6], while the magnetic field orientation was measured by [1]). The polarization angles of both sources are perpendicular to the magnetic field lines, but their motion relative to the field differs: IRS 1W moves parallel to the field, which would lead to a warping of the field lines around the bow-shock. While the turbulence at the apex tends to randomize grain orientation (and thus reduces the polarization), the concentrated magnetic field in the tails of the bow-shock may be of sufficient strength to align the grains fast enough so that they produce the observed pattern via emission or scattering. In contrast to this, IRS 21 moves perpendicular to the field, so we assume the field lines are compressed in the shock front. This would increase the field strength at the apex and produce a stronger grain alignment (and therefore polarization) there. Multiple scattering and local dichroic extinction may also play a role in both sources (depending on the dust parameters), but the extent of all these effects cannot be determined without thoroughly modeling the conditions in such a bow-shock environment.

4. Conclusions
   (i) While the foreground polarization follows the orientation of the Galactic plane on large scales in the H- and Ks-band, local deviations exist and point to the influence of magnetically aligned dust particles in the mini-spiral.
   (ii) The polarization efficiency follows a power law that matches previous models of a combination of a constant and a random alignment component along the LOS. The two sub-groups of stronger and weaker polarized sources show an offset in polarization efficiency, which supports the idea that this deviation is a local effect and not caused by a very specific and unlikely alignment of dust clouds along the LOS.
   (iii) Both bow-shock sources in the FOV show polarization (in total and resolved) consistent with emission and/or scattering on aligned dust grains. This may indicate that the local fields are strong enough to dominate grain alignment even in the turbulent bow-shock environment.

For a more in-depth analysis of the data presented here, please see [2].

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