OUTFLOWS FROM LUMINOUS YOUNG STELLAR OBJECTS: AN INFRARED POLARIMETRIC STUDY

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ABSTRACT

We present near-infrared imaging polarimetry of three regions of massive star formation, G192.16–3.82, Cep A, and W42. In W42 we have discovered a new bipolar nebula located at the far side of the H II region behind the visible cluster of exciting stars. The axis of this new nebula is aligned with the magnetic field threading the entire cluster region. Polarization in the bipolar outflow nebulousy associated with G192.16 is consistent with a single illuminating source, too faint to be detected at 2 μm. Polarization in the reflection nebulousy associated with Cep A requires more than one illuminating source, although HW 2 is clearly dominant. In all three objects, the magnetic field in the outflow at distances greater than ~0.2 pc is radial. In G192.16 the magnetic field geometry closer than ~0.2 pc to the embedded star appears chaotic. For G192.16 the outflow is not aligned with the surrounding magnetic field, which lies in the Galactic plane. In Cep A, the outflow axis could be interpreted as being aligned with the Galactic plane, but the magnetic field threading the region is not. Only in the case of W42 is the magnetic field threading the H II region aligned with the mean field in the surrounding Galactic plane.

Key words: ISM: magnetic fields — stars: winds, outflows — techniques: polarimetric

Online material: color figure

1. INTRODUCTION

Molecular outflows are a common occurrence in the evolution of young stellar objects (YSOs) of all masses (Lada 1985; Bachiller 1996). The driving mechanism for these bipolar outflows is still a subject of considerable debate, and most of our knowledge of this phenomenon is based on the study of low-mass YSOs (Cabrit et al. 1997; Shang et al. 1998). This is understandable because low-mass YSOs are more common, closer on average, and often less obscured by dust than deeply embedded, high-mass YSOs. Currently, models invoking centrifugally driven winds are a popular mechanism for driving these outflows in low-mass YSOs (e.g., Kudoh et al. 2003). In these models the magnetic field is twisted into a spiral pattern rising vertically off of the star’s dense, rotating circumstellar disk. Material entrained in this field is forced up the vertical axis and produces the observed collimated outflow (Pudritz & Ouyed 1997; Kudoh & Shibata 1997). Königl (1999) reviewed efforts to extend these magnetically driven wind models of bipolar outflows in low-mass stars to high-mass YSOs. It is not clear whether the massive outflows associated with very luminous YSOs are simply a scaled-up version of these magnetically driven winds or a completely different process.

Determining the magnetic field geometry in massive bipolar outflows could provide important constraints on these models, but this is a difficult observational task. These outflows are most easily studied when the outflow axis lies in the plane of the sky and the star’s equatorial disk is viewed nearly edge-on. This projection produces the classic bow-tie morphology seen in many sources and allows both poles of the outflow to be easily separated spatially on the sky. If dust grains in the bipolar lobes are aligned by the magnetic field in the outflow, then polarimetry of starlight shining through the outflow can measure the projected magnetic field geometry. If the pitch angle of a spiral magnetic field originating in the YSO accretion disk produces a very tight spiral, then the measured field geometry will be perpendicular to the flow (Hodapp & Eiroa 1989). Polarimetry at infrared wavelengths was used by Jones & Amini (2003) and Itoh et al. (1999) to study the magnetic field geometry in the massive molecular outflow associated with DR21. Most of their observations were consistent with a magnetic field pointing radially outward, aligned with the axis of the outflow.

A similar conclusion was reached by Hodapp (1990) using optical polarimetry of stars in the vicinity of Cep A. However, optical polarimetry cannot penetrate deep into obscured regions and is more likely to measure the larger scale magnetic field geometry in which the star formation region is embedded. Infrared (IR) polarimetry has the advantage of being able to penetrate the considerable dust extinction that typically accompanies deeply embedded massive YSOs (Hodapp & Eiroa 1989). This allows us to probe lines of sight more likely to pass through the denser portions of the outflow. Imaging polarimetry provides additional information on the reflection nebulosity produced by the bipolar outflow. Furthermore, at IR wavelengths reflection nebulosity in heavily obscured regions close to the driving stellar source can be probed.

Polarimetry at longer wavelengths, where the aligned dust grains are in emission, avoids the need for background field stars. However, millimeter and submillimeter polarimetry of regions with one or more massive outflows are sensitive to the magnetic field geometry associated only with warm dust near the massive YSOs, not the more distant dust in the bipolar outflow. Greaves et al. (1997) found a rough correlation between the position angle (P.A.) of the magnetic field in the warm dust centered on the YSO and the direction of the outflow. When the outflow lies in the plane of the sky, the magnetic field tends to be perpendicular to the outflow axis, just the opposite of what is found farther out in the outflow (Jones & Amini 2003; Itoh et al. 1999).

In this paper we use imaging polarimetry at H (1.65 μm) and K (2.2 μm) of three compact regions with massive star
formations: G192.16–3.82, W42, and Cep A. G192.16 and Cep A are well-known outflow systems, and Cep A has had optical and near-IR polarimetry of surrounding stars (Hodapp & Eiroa 1989; Hodapp 1990). W42 was not previously known to contain an outflow, but we have discovered a very reddened, elongated reflection nebula in the cluster indicative of a bipolar outflow. For all three systems we present IR polarimetry of stars within and near the central star-forming region and imaging polarimetry of the reflection nebula associated with the outflow.

2. OBSERVATIONS

All observations were made with NSFCAM (Shure et al. 1994) in polarimetry mode on the NASA IRTF 3 m telescope at a plate scale of 0.03 pixel$^{-1}$, resulting in a field of view 77'' square. In polarimetry mode NSFCAM utilizes a rotating half-wave plate at the entrance window of the camera and a wire grid polarizer in the secondary filter wheel. This allows the observer to form images at polarization position angles of 0°, 45°, 90°, and 135° on the sky. From these we compute Stokes quantities $Q$ ($I_0 - I_90$) and $U$ ($I_{45} - I_{135}$) for stars and nebulosity within the image. Details of the NSFCAM (plus polarimeter) technique are given in Jones (1997), Jones & Gehrz (2000), and Kelley et al. (2004). Table 1 summarizes observational details and parameters of our targets.

Photometric and instrumental polarization calibrations were achieved by observing stars from the list of Elias et al. (1982). Unreddened early-type stars in this list were assumed to have no polarization at the 0.1% level. Measurements of several of these stars indicate that the instrumental polarization is less than 0.1%. Because our technique requires a finite time between wave-plate positions, sky and transmission fluctuations create systematic errors for single measurements at the ±0.2% level. These systematic effects are the primary source of error for bright objects. P.A. and polarization efficiency calibrations were made by observing S1 in $ho$ Oph, which was assumed to have $P_H = 3.9\%$, $\theta_H = 28^\circ$ and $P_K = 1.95\%$, $\theta_K = 28^\circ$. Additional checks on the P.A. calibration were provided by observing BN in Orion and AFGL 2591. Photometric magnitudes were transformed from the natural IRTF system (Tokunaga et al. 2002) to the modern MKO system using the transformation relations described in Kelley et al. (2004).

Our ability to measure the polarization for stars depends on three factors. If the star is very faint, it will be impossible to measure the fractional polarization, given the typical values of a few percent for interstellar polarization. If the star is very bright, but has a very low intrinsic polarization, it will also be impossible to measure the polarization. Finally, stars with images confused with nearby stars, stars in the negative (sky) beam, or stars embedded in bright nebulosity will also be impossible to accurately measure. In this paper we report polarimetry of stars only if the signal-to-noise ratio for the fractional polarization ($P/\sigma_P$) is greater than 3.

### TABLE 1

| Object          | Date       | Filters | Mode      |
|-----------------|------------|---------|-----------|
| G192.16 core, east | 2002 Feb 14 | $K$     | Polarimetry |
| G192.16 west    | 2002 Feb 15 | $K$     | Polarimetry |
| W42            | 2003 Jul 10 | $H$, $K$ | Polarimetry |
| Cep A          | 2003 Jul 9  | $K$     | Polarimetry |
| Cep A          | 2003 Jul 10 | $H$     | Polarimetry |

3. DISCUSSION

3.1. Grain Alignment

Interstellar polarization has long been attributed to the alignment of interstellar grains through some interaction with the magnetic field, such as a modified form of the classic Davis-Greenstein mechanism (Davis & Greenstein 1951). There is little doubt that in the diffuse ISM between stars magnetic alignment of some sort is the principal mechanism at work (for a review of grain alignment, see Jones 1996; Lazarian 2003). This conclusion is based on the pattern of optical polarization vectors in the Milky Way (Heiles 2000) and comparisons between Faraday studies at radio frequencies and optical/IR polarimetry in external galaxies (Jones 1996). However, in specific locations not probed by these tests, other mechanisms might be dominant. These include the original mechanical mechanism of Gold (1952) that used streaming motions of the gas, as well as more advanced treatments (Lazarian 1995) and magneto-mechanical mechanisms such as ambipolar diffusion (Roberge et al. 1995).

Although there is no direct evidence for grain alignment by these mechanical mechanisms at this time, one location where they might be expected to play a role is in the outflows from massive YSOs, which will certainly have significant streaming motions in the gas. The direction of grain alignment (long axis) for the original Gold mechanism is along the direction of the flow. This is perpendicular to the grain alignment we find based on polarimetry of background stars shining through the outflows discussed below. However, not all alternatives to the Davis-Greenstein mechanism align the grains in this manner. With the caveat that other alignment mechanisms may play a role in massive YSO outflows, in this paper we assume magnetic grain alignment by some modified version of the Davis-Greenstein mechanism (Jones 1996), where the direction of the polarization vector for light in extinction corresponds to the magnetic field direction.

3.2. G192.16–3.82

G192.16 has been extensively studied in CO (Snell et al. 1990; Shepherd et al. 1998), other molecules (Molinari et al. 1996), maser emission (Codella et al. 1996), and near-IR imaging (Hodapp 1994). Molecular line maps show a single bipolar outflow from a young star, most likely not confused with other outflows, extending 1″–2″ to the east and west at a P.A. close to 90°. There is an infrared reflection nebula that coincides with the molecular outflow (Hodapp 1994). The outflow is centered on IRAS 05553+1631, which is coincident with a centimeter and millimeter continuum source (Shepherd & Kurtz 1999; Shepherd et al. 2002). The radio continuum fluxes are consistent with an early B star at a distance of 2 kpc (Shepherd et al. 1998). High angular resolution centimeter and millimeter continuum observations show evidence for a solar system–size accretion disk surrounding the exciting star (Shepherd et al. 2002). G192.16 has a very long bipolar outflow, about 3 pc, with Herbig-Haro objects extending up to 10 pc from the star (Devine et al. 1999).

Our K-band image of G192.16 core and portions of the outflow to the east and west is shown in Figure 1. The K-band polarization vectors of six stars located along the line of sight are shown in the top panel of Figure 1. The coordinates and polarization of these stars are listed in Table 2. The centimeter and millimeter continuum source believed to correspond to the central source of the outflow is located just to the west of the bright reflection nebula in the central image and is marked by
a white cross. The white patches in Figure 1 are due to stars in the negative (sky) beam.

The polarization of stars seen toward G192.16 on the sky is shown in the larger context of the surrounding ISM in Figure 2, where we include two stars (7 and 8) well off the outflow axis to the south (also listed in Table 2). These two stars have polarization vectors closely aligned with the Galactic plane at a P.A. of 140°. For the distance and direction of G192.16, we are looking largely across spiral arms in the Milky Way and would expect the magnetic field to lie predominately in the

![Image](gray-scale-image-of-G192.16-3.84-at-K-2.2-µm.jpg)

**Fig. 1.** Gray-scale image of G192.16—3.84 at K (2.2 µm). The location of the millimeter point source is indicated by a white cross. White objects in the frames are due to stars in the sky beam. The top panel has the polarization vectors for six of the stars listed in Table 2 superposed on the image. The bottom panel has the polarization vectors for the reflection nebulosity measured at different locations in the outflow and listed in Table 3. All of the polarization vectors are consistent with light scattered from a single source located at the position of the millimeter continuum source.

![Image](polarization-of-stars-nearby-and-south-of-G192.16-3.84.jpg)

**Fig. 2.** Polarization of stars nearby and south of G192.16—3.84. The cross indicates the location of the millimeter continuum source identified as the YSO powering the outflow. The molecular outflow is aligned roughly east-west. The Galactic plane lies at a P.A. of 120°. Note that the position angles of the two stars to the south (Table 2) show that the surrounding interstellar magnetic field lies in the Galactic plane. However, the stars close to G192.16 are clearly at very different position angles than the magnetic field in the surrounding diffuse ISM.

| Star | R.A. (J2000) | Decl. (J2000) | $P_K$ (%) | $\epsilon_P$ (%) | $\theta_K$ (deg) |
|------|--------------|--------------|-----------|-----------------|------------------|
| 1.... | 05 58 19.3   | +16 32 30    | 1.6       | 0.3             | 52               |
| 2.... | 05 58 15.6   | +16 32 19    | 2.3       | 0.3             | 93               |
| 3.... | 05 58 14.6   | +16 31 55    | 1.5       | 0.3             | 155              |
| 4.... | 05 58 15.2   | +16 31 39    | 1.3       | 0.3             | 87               |
| 5.... | 05 58 15.7   | +16 31 37    | 1.9       | 0.3             | 35               |
| 6.... | 05 58 11.2   | +16 31 21    | 2.6       | 0.8             | 178              |
| 7.... | 05 58 14.3   | +16 30 00    | 1.8       | 0.4             | 141              |
| 8.... | 05 58 10.0   | +16 30 04    | 2.2       | 0.5             | 138              |

**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
plane (e.g., Jones 1996). Examination of this region of the sky in the large database of optical polarimetry of stars compiled by Heiles (2000) also shows that the interstellar polarization vectors lie in the plane of the galaxy. Thus, G192.16 is embedded in a large-scale magnetic field aligned with the Galactic plane. The outflow axis of G192.16 is not aligned with the surrounding magnetic field but is oriented at a significant angle of ∼50° to the Galactic plane.

With one exception (star 3), polarization vectors for the six stars in the same region of the sky as the outflow are not aligned with the interstellar magnetic field. This strongly suggests the interstellar polarization of these stars is influenced by dust associated with G192.16. Stars 1 and 6 are ∼1′ northeast and southwest of the core, respectively, and have polarization vectors pointing radially away from the central source. These stars are likely sampling the magnetic field geometry in the outflow, indicating that at a projected distance of 0.6 pc from the embedded YSO the magnetic field is largely radial, as was the case for DR21. However, within a projected distance of a few tenths of a parsec, the polarization vectors are more chaotic. Star 3 is aligned with the local ISM and may be a foreground object, but the other three stars show no simple pattern of polarization position angles. Unlike the DR21 outflow, where the observations were consistent with a purely radial field geometry everywhere in the outflow, the magnetic field geometry close to the exciting star in G192.16 must be more complex.

Deep, high-resolution imaging of the region surrounding the YSO at 2.1 μm has been reported by Indebetouw et al. (2003). They find a faint 2 μm source about 1″ east of the radio and millimeter continuum source. The K-band flux from this source shows little evidence for Brγ or shocked molecular hydrogen emission. The source is essentially undetected at H (1.65 μm), indicating that it is very red. Indebetouw et al. (2003) speculate that this source is either directly viewed photospheric emission from the central star or a bright knot of diffuse emission associated with the accretion disk. Below we examine the imaging polarimetry of this source and try to determine its true nature.

K-band polarimetry of the reflection nebulosity associated with the G192.16 outflow is illustrated in the bottom panel of Figure 1 and listed in Table 3. These measurements were made using a synthetic 4.5″ × 4.5″ aperture with our I, Q, and U images. All of the polarization vectors are consistent with simple scattering of light from a central illuminating source close to the location of the centimeter and millimeter continuum source. In Figure 3 we examine the region of bright nebulosity close to the illuminating source in more detail. The top left panel in Figure 3 shows a gray-scale image of the inner region. Here we see a bright patch of reflection nebulosity and a fainter source, indicated by the cross lines, about 3″ west of the bright peak. This fainter source is the source discovered by Indebetouw et al. (2003), who had significantly better seeing (0.′6) than in our image (1.′7). Based on our astrometry using POSS stars in the vicinity of G192.16, the faint source is located at R.A. = 05h58m13.6, decl. = +16°31′58″ ± 1″ (J2000), in excellent agreement with Indebetouw et al. (2003).

Using a 1″5 × 1″5 synthetic aperture we made polarization measurements of the nebulosity shown in Figure 3. The results of these measurements, uncorrected for seeing effects, are shown in the bottom left panel of Figure 3. The source discovered by Indebetouw et al. (2003) is highly polarized and is very likely reflection nebulosity, not the central star itself. Because of seeing effects, flux from the brighter patch of nebulosity can contaminate the polarized intensity we measure for nearby regions. We can roughly subtract this contamination from patches nearby the bright source by using the point-spread function of nearby stars to estimate the amount of flux underlying the patch of sky we are trying to measure. For the faint source, contamination from the bright patch was about 30% of the total intensity. When the correction is made to I, Q, and U, we obtain the polarization vectors in the bottom right panel of Figure 3. These vectors point back to an illuminating source that is 1″5 ± 1″0 west of the suspected stellar source. Within our estimated position error of 1″, this is also the location of the compact continuum source. We conclude that the massive YSO responsible for the molecular outflow and the illumination of the nebulosity in G192.16 is coincident with the centimeter and millimeter continuum source and is not visible at K.

Our images are sufficiently deep to put new constraints on the extinction in front of the central star. In areas of our images well away from bright nebulosity, our 3 σ detection limit is about K = 18. Near the position of the exciting star, however, we are limited to about K = 16.5 because of the bright underlying nebulosity. We estimate that the central star must be fainter than this limit. Using the expected value for the apparent K magnitude of a B2 star at 2 kpc suggested by Indebetouw et al. (2003) of K = 9.7, we derive AK ≥ 6.8. On the basis of the extinction law from Rieke & Lebofsky (1985), this corresponds to greater than 65 mag of extinction at V. The infrared color for this amount of extinction is E(H − K) ≥ 4.2, placing the H-band brightness of this star well out of reach of our observations.

### Table 3

| Patch | R.A. (J2000) | Decl. (J2000) | PK (%) | θK (deg) |
|-------|--------------|---------------|--------|----------|
| 1...... | 05 58 18.4   | +16 31 51     | 45     | 12       |
| 2...... | 05 58 16.1   | +16 31 49     | 35     | 12       |
| 3...... | 05 58 15.8   | +16 31 51     | 39     | 15       |
| 4...... | 05 58 13.8   | +16 31 57     | 37     | 11       |
| 5...... | 05 58 12.9   | +16 31 53     | 18     | 165      |
| 6...... | 05 58 12.3   | +16 32 15     | 31     | 46       |
| 7...... | 05 58 12.3   | +16 32 00     | 17     | 7        |
| 8...... | 05 58 11.8   | +16 31 39     | 62     | 138      |

### 3.3. W42

W42 (=G25.4−0.25) is a moderately compact, obscured H II region toward the inner Galaxy at l = 25°. Continuum radio maps at 5 GHz were made by Woodward et al. (1985), which showed an elongated emission structure with two cores smaller than the 6″ beam. At the 5 kpc distance they adopted, the radio continuum observations were consistent with an O6.5−7 star as the primary ionizing source. Blum et al. (2000) surveyed the stellar content of W42 with imaging and spectroscopy in the near-IR. They found a cluster of stars with a K-band luminosity function similar to the Trapezium. The H II region is powered by a single star that they classify as O5−6.5, based on the classification system of Hanson et al. (1997). Blum et al. (2000) suggest a closer distance of ∼3 kpc, based on spectroscopic parallax arguments applied to the O star and its dereddened K magnitude (see also Lester et al. 1985). The spectrum of other bright stars in the cluster are featureless, suggesting that they are still YSOs.
Our $K$-band image of W42 is shown in Figure 4 along with the polarization vectors of 14 stars located along a line of sight to the H II region. The coordinates and polarization data for these stars are listed in Table 4. Note that the polarization vectors are relatively uniform in P.A. There is no evidence for more than one component to the magnetic field sampled along the line of sight to W42. The stars within 30\degree of the exciting O star (star 12 in Table 4 and star 1 in Blum et al. 2000) have a mean P.A. of 18\degree, with a dispersion of 12\degree. The stars to the east and west of the central cluster have a P.A. that lies in the plane of the Milky Way at about 28\degree. This is also the P.A. of the long axis of the continuum radio emission observed by Woodward et al. (1985).

Woodward et al. (1985) speculate that the elongated radio emission may be indicative of a bipolar source. Although there is no bipolar nebula clearly visible in either our $K$-band image or the images in Blum et al. (2000), close examination of the polarimetry does indeed reveal a bipolar nebula. In the left panel of Figure 5 we show a gray-scale image of the inner 30\degree of the H II region in total intensity in the $K$ band. In the right panel we show an image in polarized intensity $IP = (Q^2 + U^2)^{1/2}$, with the polarization vectors for five regions of highly polarized nebulosity superposed. These five regions were measured using a synthetic aperture $2''7 \times 2''7$ in size (see Table 5). Highly polarized reflection nebulosity, almost unrecognizable in the total intensity image, is clearly visible in the polarized intensity image. The polarization vectors are consistent with an illuminating source located between the two brightest blobs of nebulosity, indicated by the cross marks on the right and bottom of the polarized intensity image. If there is a luminous YSO located between the two bright blobs of reflection nebulosity, it would have coordinates R.A. = 18h38m14.6s, decl. = +06\degree48\arcmin00\arcsec (J2000). The long axis of the reflection nebulosity is oriented at about 15\degree, essentially the same orientation as the magnetic field through the entire cluster.

The newly discovered bipolar outflow is very heavily reddened by extinction. The $H - K$ color of the two brightest blobs is $H - K \sim +2.4$, redder than any of the surrounding stars (Fig. 4 in Blum et al. 2000). Since reflection nebulosity can be intrinsically much bluer than $H - K = 0.0$ (depending on the ratio of extinction in the $K$ and $H$ bands), the reddening must be very large. The extinction to the excitation source is likely to be even greater than this. This is consistent with the presence of young stars in the cluster, which are known to produce significant extinction. The outflow, which is evident in the $K$-band images, is likely to be driven by the ultraviolet radiation from these stars, which heats the surrounding gas and drives it outwards. The outflow extends several parsecs in length, as seen in the polarized intensity image.
on the spectral energy distribution of the illuminating star), our measured color translates to a visual extinction of $A_V \approx 5.5$. The illuminating star is presumably behind additional dust associated with an equatorial accretion disk, explaining why it is not visible at $K$. Blum et al. (2000) argue that we see the association and its primary O star on the front side of a dense, molecular cloud. The newly discovered bipolar nebula is clearly deeper into this denser region than the cluster, indicating ongoing star formation just behind the interface between the H II region and the molecular cloud. This reminds us of the Trapezium, which has a comparable luminosity and a similar geometry with respect to our line of sight from the Earth.

Optical polarimetry of stars in the surrounding sky taken from the compilation of Heiles (2000) clearly shows a general magnetic field direction in the diffuse ISM surrounding W42 that lies in the plane of the Galaxy at P.A. = 28°. The magnetic field threading W42 is close to this P.A. We are presented with a picture of a very uniform magnetic field geometry threading through the entire cluster and linking up smoothly with the field in the surrounding diffuse ISM. The newly discovered bipolar nebula has a long axis aligned in the same direction as the threaded magnetic field, indicating that the polar axis of the illuminating star is also aligned with the local magnetic field. This is in contrast to G192.16 and DR21, where the axis of the bipolar nebula and the magnetic field in the outflow is well away from alignment with the Galactic plane.

### 3.4. Cep A

Cep A east contains a well-studied, relatively nearby molecular outflow driven by one or more massive, very young stars. At a distance of 725 pc (Blauw et al. 1959) the far-IR
luminosity is about $2.4 \times 10^4 L_\odot$, which is consistent with several early B stars. The bipolar outflow is quite complex (Torrelles et al. 1993; Narayanan & Walker 1996) and is suggestive of multiple outflow sources. The molecular line observations have also been interpreted as clumps in two sides of a poorly collimated bubble powered by one or more YSOs (Corcoran et al. 1993).

Radio continuum observations at a resolution of 1" (Hughes & Wouterloot 1984) reveal several compact sources, which Hughes & Wouterloot associate with early B stars. Source number 2 in their map, commonly referred to as HW 2 in the subsequent literature, is usually considered to be the primary source of the outflow. This source was undetected at $K$ by Casement & McLean (1996), who present imaging polarimetric observations of Cep A on a 2" grid at $J$, $H$, and $K$. Analysis of the highly polarized reflection nebulosity surrounding HW 2 allowed Casement & McLean (1996) to show that the origin of the scattered light from dust in the outflow is primarily from HW 2. They also found that within 10"–15" of HW 2, the polarization vector pattern was more complex than simple single scattering and clearly required multiple scattering.

Goetz et al. (1998) made a detailed study of Cep A east using broad- and narrowband imaging from 1.4 to 5 $\mu$m. They find two regions of shock-excited line emission, one 20" to the northeast of HW 2 and one 20" to the east-southeast of HW 2.

They identify HW 3 (not HW 2) as the primary driving source of the shock emission to the east-southeast and consequently favor a multiple outflow model. They find that the reflection nebulosity to the northeast of HW 2 and HW 3 is exceptionally red in their $K$ – $L'$ image, indicating it is behind significant extinction. Goetz et al. (1998) were unable to detect HW 2 at $L'$ or $M$, implying $A_V > 200$ if it is a bare B1 star. In their schematic diagram of the Cep A region, Goetz et al. (1998) associate the rotating core observed in CS line emission by Narayanan & Walker (1996) with a “fluffy torus” centered on HW 2 and oriented at a P.A. of about 135°.

Glenn et al. (1999) measured the polarization toward HW 2 at 1.3 mm and found the magnetic field was oriented at 170°, which is roughly perpendicular to the outflow axis. This result is consistent with the conclusion of Greaves et al. (1997), who argue that when the bipolar outflow lies in the plane of the sky, the magnetic field observed at the far-IR/submillimeter peak is perpendicular to the outflow axis. Hodapp (1990) observed $I$-band polarimetry of nearby stars and found the magnetic field geometry 1°–4' away from HW 2 was inconsistent with a single component. Unlike G192.16 and W42, the optical polarimetry of stars within a few degrees of Cep A does not present a clear picture of the surrounding interstellar magnetic field. Using the database of interstellar polarimetry compiled by Heiles (2000), we plot the polarization vectors for stars within a few degrees of Cep A in Figure 6. South of the star-forming region the polarization vectors are nicely aligned with the Galactic plane, indicating the interstellar magnetic field lies in the plane along that line of sight, as expected. However, 1° north and west, some stars show interstellar polarization vectors that lie in the plane of the Galaxy, while others lie at a P.A. of about 125°. We will argue below that the foreground interstellar magnetic field is aligned with the plane of the Milky Way disk (P.A. = 65°), the magnetic field threading the Cep A complex is almost perpendicular to the plane (P.A. = 125°), and the magnetic field in the outflow is radial with respect to HW 2/3.

A false-color image of Cep A using our $H$- and $K$-band images is shown in Figure 7. The location of HW 2 is shown as

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**TABLE 5**

**REFLECTION NEBULOSITY IN W42**

| Patch | R.A. (J2000) | Decl. (J2000) | $P_K$ (%) | $\theta_K$ (deg) |
|-------|--------------|--------------|-----------|-----------------|
| 1..... | 18 38 14.69  | ~06 47 54    | 13        | 100             |
| 2..... | 18 38 14.66  | ~06 47 57    | 32        | 97              |
| 3..... | 18 38 14.55  | ~06 48 02    | 20        | 97              |
| 4..... | 18 38 14.50  | ~06 48 06    | 20        | 106             |
| 5..... | 18 38 14.47  | ~06 48 11    | 26        | 101             |
a cross. The reddest tones correspond to \( H - K = +4.0 \), and the bluest tones correspond to \( H - K = +1.75 \), which is still quite red. Several stars are bluer than \( H - K = +1.75 \), and they are saturated at a blue color. Depending on the intrinsic colors of the illuminating source, the \( H - K \) color of reflection nebulosity would usually be significantly bluer than any of the values we measure in Cep A. The entire reflection nebulosity must be behind significant interstellar extinction, very likely associated with the star-forming region itself. This intervening extinction is optically thickest close to the central source and becomes thinner as one moves north and east from the massive YSO. A similar conclusion was reached by Goetz et al. (1998) from their \( K - L' \) image.

In Figure 8 we plot a number of features seen in Cep A over an underlying gray scale of the \( K \)-band intensity. The solid contours are from the radio continuum map of Hughes & Wouterloot (1984). Their source 2 (HW 2) is associated with the primary central massive YSO that powers and illuminates the outflow. The narrow rectangles are the polarization vectors of the reflection nebulosity on a 2" grid. The solid black lines are the \( H \)-band polarization vectors of the five stars listed in Table 6. The P.A. of the Galactic plane is 65°, very close to the P.A. of star 4.

Based on the \( H - K \) colors we observe for the nebulosity, the extinction within 10″–15″ of HW 2 is too great for background

Fig. 6.—Optical polarimetry of stars within a few degrees of Cep A (cross) taken from the compilation of Heiles (2000). The Galactic plane is indicated by the dashed line.

Fig. 7.—False-color image of the Cep A outflow from \( H \)- and \( K \)-band images. The cross indicates the location of the primary illuminating source. The reddest tones (middle of image) correspond to \( H - K = +4.0 \). The bluest tones (toward left) correspond to \( H - K = +1.75 \). Stars with \( H - K \) colors bluer than +1.75 are saturated at the bluest color. The reflection nebulosity is clearly much more heavily reddened near the central star. [See the electronic edition of the Journal for a color version of this figure.]
stars to shine through (see Goetz et al. 1998). Star 1 in Table 6 is outside the bright nebulosity and is relatively red. It has a P.A. very close to the position angles measured by Hodapp & Eiroa (1989) in the H band for stars a few arcminutes north and northwest of star 1. We hypothesize this star is either embedded within the Cep A complex or, less likely, shining through from behind. This would imply that the interstellar magnetic field in the immediate vicinity of Cep A is at a P.A. of ~125° (Hodapp & Eiroa 1989).

Star 2 is much bluer than star 1 and has a similar P.A., but it is still outside the bright nebulosity and may also be sampling aligned grains in Cep A. Star 3 is much bluer than the underlying reflection nebulosity and cannot be shining through the outflow. The polarimetry of star 3 is sampling the magnetic field geometry well in front of the outflow and is consistent with a foreground field lying in the plane of the Galaxy. Stars 4 and 5 are only slightly bluer than the underlying nebulosity and are probably sampling aligned grains associated with the near side of the Cep A outflow. The polarimetry of star 4 could be interpreted in two ways. It could be dominated by the foreground extinction, causing the P.A. to lie in the plane. But, the P.A. points directly back to HW 2/3 and could be indicative of a magnetic field in the outflow pointing radially to the exciting B stars. The P.A. of star 5 also points directly back to HW 2/3 and is most likely sampling the magnetic field in the outflow as well. Note that Hodapp (1990) and Hodapp & Eiroa (1989) measured several stars 1'–2' east of star 5, all of which have position angles very similar to star 5. We argue that the magnetic field in the outflow at a distance greater than 20'' from the cluster of massive YSOs is radial.

![Fig. 8.—Gray-scale image of Cep A at K. The solid contours are the radio continuum observations of Hughes & Wouterloot (1984). Their source 2 (HW 2) is associated with the central star powering and illuminating the outflow. The thin rectangles are the polarization vectors of the nebulosity measured on a 2'' grid spacing. The polarization vectors of the five stars in Table 6 are plotted as solid black lines.](image)

| TABLE 6 | STARS IN CEPHEUS A |
|---------|---------------------|
| Star    | R.A. (J2000) | Decl. (J2000) | H–K   | $P_H$ (%) | $\epsilon_P$ (%) | $\theta_H$ (deg) |
| 1       | 22 56 16.0 | +61 02 19 | 2.75  | 5.9      | 0.2     | 123         |
| 2       | 22 56 17.3 | +61 02 24 | 0.73  | 0.9      | 0.2     | 154         |
| 3       | 22 56 19.8 | +61 02 21 | 0.61  | 0.8      | 0.2     | 54          |
| 4       | 22 56 22.5 | +61 02 01 | 1.39  | 4.9      | 0.3     | 63          |
| 5       | 22 56 22.6 | +61 01 42 | 1.45  | 2.1      | 0.3     | 94          |
A polarization map at a spatial resolution of 0.9\arcsec is shown in Figure 9. The polarization vectors for the reflection nebulosity are dominated by single scattering directly from the central sources at distances of more than 500–1000 from HW 2/3. The polarization vectors to the north and west of the embedded stars are consistent with scattering of light only from HW 2. The polarization vectors to the northeast and east, however, are illuminated from a location about 5\arcsec southeast of HW 2. We do not see evidence for this at a coarser grid spacing in the polarization map of Casement & McLean (1996). Our polarization map requires more than one source of light being scattered by dust in the Cep A outflow. Dust in the outflow to the north and west is illuminated only by the YSO associated with HW 2. The dust in the outflow to the northeast and east is seeing at least one additional source to the southeast of HW 2, perhaps source HW 3. Goetz et al. (1998) associate the shocked gas coincident with HW 7 in the radio map with outflow from HW 3, not HW 2. Note that both the axis of the elongated radio emission in HW 7 and the polarization vector for star 5 point directly back to HW 3. It may be that HW 3 has brightened at near-IR wavelengths since the observations of Casement & McLean (1996) and is now contributing more to the reflection nebulosity.

The polarization vectors strongly depart from simple centrosymmetric scattering along a band stretching across HW 2 from the southeast to the northwest at a P.A. of ~135\degree. This morphology corresponds well in P.A. to the smaller fluffy torus described in Goetz et al. (1998) and the rotating gas described by Narayanan & Walker (1996). Casement & McLean (1996) conclude that this departure from centrosymmetric scattering is likely due to multiple scattering in dust near the central source. We are probably looking through an optically thick disk of material extending at least 15\arcsec (0.05 pc) to the northwest and southeast of the central cluster of B stars. Light passing through this region will be scattered at least twice and lose the simple centrosymmetric polarization pattern produced by single scattering.

Based on all of the available observations of interstellar polarization toward Cep A, we propose the schematic picture of the magnetic field geometry within and in front of Cep A shown in Figure 10. The foreground (and possibly background) magnetic field is closely aligned with the Galactic plane at a P.A. of ~65\degree. The field threading the overall star-forming complex is at a very different orientation of ~125\degree. At the far-IR/submillimeter peak, essentially at the location of HW 2 and HW 3, the magnetic field is roughly perpendicular to the outflow at ~170\degree. We say roughly, because there are probably multiple outflows and the reflection nebulosity presents a very broad fanlike structure on the sky. Note, however, that the field direction at the far-IR/submillimeter peak is perpendicular to the outflow axis in the model proposed by Narayanan & Walker (1996). Finally, the interstellar polarization to the east.
of the core cluster, as measured by Hodapp and ourselves, shows that the magnetic field well out in the outflow is radial.

4. CONCLUSIONS

We have made imaging polarization observations of three regions of massive star formation at near-IR wavelengths. These observations allowed us to measure the interstellar polarization of stars and submillimeter polarimetry centered on the central cluster of massive YSOs.

4.1. Reflection Nebulosity

The reflection nebulosity in G192.16 was bright enough in several locations for us to measure the polarization due to scattering of light from the central YSO by dust in the outflow. The observed polarization is entirely consistent with illumination by a single stellar source. This position of this object is coincident with the well-studied pointlike centimeter and millimeter continuum source previously identified as the illuminating YSO. The YSO is undetected in our maps at 2 μm down to $K = +16.5 \ (3 \sigma)$.

In Cep A, the polarization map of the reflection nebulosity shows evidence for more than one source of illumination in addition to HW 2, possibly HW 3. Neither of these sources are detected at 2 μm in our maps. The polarization in the reflection nebulosity close to HW 2 and stretching from HW 2 for several arcseconds perpendicular to the outflow shows clear evidence of multiple scattering. This region probably contains the outer extremes of a large accretion disk surrounding HW 2.

4.2. The Magnetic Field Geometry

In W42 and Cep A, the main axis of the outflow and the local magnetic field are within 15° of the Galactic plane. In G192.16, the main axis of the outflow and the magnetic field in the outflow are misaligned by at least 60° with respect to the Galactic plane. In W42 the magnetic field threading the H ii region is well aligned with the Galactic plane and shows no evidence for additional components to the magnetic field geometry. The magnetic field geometry within Cep A is complicated, but we believe the field threading the complex is not aligned with the Galactic plane, even though the outflow axis may be. In G192.16, the magnetic field geometry threading the compact H ii region could not be determined.

In all three regions, the local magnetic field is aligned with the direction of the outflow at distances of several tenths of a parsec and farther from the central source. In G192.16 the magnetic field geometry closer than a few tenths of a parsec to the central source is probably chaotic and does not exhibit a radial geometry. In Cep A, we have no observations of the magnetic field geometry within 20° of the exciting star(s), but submillimeter observations indicate that the field at the location of the embedded YSO(s) is perpendicular to the outflow axis. In W42, the newly discovered bipolar nebula is too small in angular extent on the sky for our technique to be able explore the embedded magnetic field geometry. The axis of the nebula is, however, exactly aligned with the magnetic field in the H ii region and the Galactic plane.

The magnetically driven model for YSO outflows predicts a spiral magnetic field in the core of the outflow along the outflow axis. Our observations do not rule this model out if the field is a tight spiral only at small distances of less than ~0.2 pc from the star. At greater distances, our observations are consistent with a purely radial field. The tendency for the magnetic field at the location of the embedded YSO(s) (measured by submillimeter polarimetry) to lie perpendicular to the flow is probably due to a toroidal field in the extended equatorial disk, not in the outflow itself (see the various model geometries discussed in Greaves et al. 1997). Neither our technique of measuring interstellar polarization of background stars nor submillimeter polarimetry with large beam sizes will be able to probe the magnetic field geometry in the outflow close to but separated from the embedded star and its accretion disk. High spatial resolution far-IR and millimeter polarimetry will be necessary.

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