Polarimetry of the Interstellar Medium
ASP Conference Series, Vol. 97, 1996
W. G. Roberge and D. C. B. Whittet, eds.

Magnetic Fields in Star-Forming Regions — Near-Infrared and Submillimeter Approaches

M. Tamura and S. Hayashi

National Astronomical Observatory, Mitaka, Tokyo 181, Japan

Y. Itoh

University of Tokyo, Bunkyo, Tokyo 113, Japan

J. H. Hough and A. Chrysostomou

University of Hertfordshire, Hatfield, Hertfordshire AL10 9AB, UK

Abstract. In order to study the magnetic field structure in star forming regions on various scales, we have been conducting both near-infrared and submillimeter polarimetry toward nearby molecular clouds. The near-infrared approach is the polarimetry of either background or embedded sources in molecular clouds, useful to trace the magnetic field structure in the clouds and cloud cores. The submillimeter approach is the polarimetry of dust thermal emission from the circumstellar structure around young stellar objects, invaluable to trace the magnetic field in disks/envelops. In this paper, we present results of Kn (2.15 μm) and H (1.65 μm) band polarimetry of the ρ Ophiuchi core obtained with an infrared array detector as well as results of 1100 and 800 μm polarimetry of young stellar objects in a number of star forming regions.

1. Introduction

Magnetic fields are believed to play an important role in star formating processes. However, observations of magnetic fields in star forming regions have been relatively limited. Optical polarimetry of background stars shining through the periphery of dark clouds has successfully traced the magnetic field structure of the *outer part* of the clouds (e.g. Vrba et al. 1976). Near-infrared polarimetry of background/embedded stars shining through the central region the central region if the clouds has also been used to trace the magnetic field structure *inside* the dark cloud (Tamura et al. 1987, 1988; Sato et al. 1988). However, these observations cannot reveal the small scale field structure of the cloud core embedding young stellar objects, because of the heavy extinction in the optical case and the limited sensitivity of the single channel IR detector in the IR case. Recent progress of the array detectors at NIR wavelengths enable us to make polarimetry of fainter sources and go deeper inside the dark clouds. In addition, availability of large-aperture submillimeter telescopes allow *thermal* polarization measurements at a wavelength of about 1 mm. This enables us to reveal the magnetic field structure in such dense regions as disks/envelopes (Hildebrand 1988). By combining these near-infrared and submillimeter approaches, we can trace the magnetic field on scales of dark clouds and cloud cores to circumstellar disks/envelopes. For this aim, we have been conducting both near-infrared array polarimetry and submillimeter of star forming regions.

2. Observations

Near-infrared polarizations of the ρ Ophiuchi core were measured at the 3.9 m AAT, in Australia, using the IRIS 128×128 HgCdTe camera and the IRISPOL polarimeter module. We used Kn (2.15 μm) or H (1.65 μm) band filter, depending on the brightness of each source.

The submillimeter polarimetry observations of young stellar objects in a number of star forming regions were made on the 15 m JCMT at Mauna Kea, Hawaii, using the single channel bolometer and the Aberdeen/QMC polarimeter. We used a 1.1 mm or a 0.8 mm filter, depending on the weather condition. The beam size was about 19″.

3. Results and Discussion

3.1. Near-Infrared Results - ρ Oph Core

We have observed more than 45 sources, all of which are embedded sources (Greene & Young 1992). All these sources are polarized at a level of $1 - 20\%$, up to 40%. Some of the sources with a relatively high polarization are due to reflection nebulosity associated with the YSOs. Since our data are imaging polarimetry, we can estimate the contribution of the reflection nebula to the observed polarization and separate the contribution from the dichroic absorption along the same line-of-sight. Generally, the effect of reflection nebulosity is small (since the nebula shows a circular symmetry), and most of the observed polarizations represent the magnetic field direction within the ρ Oph core. The polarization map is shown in Fig. 1, overlaid on the high-resolution molecular ($C^{18}O$ J=1–0) map of the cloud core by Umemoto et al. (1995, in prep.).

In the southern part of the core, the polarization vectors, therefore the magnetic field direction, are very well aligned at the position angle of about 50°, consistent with the results of Sato et al. (1988). One should note a clear perpendicularity between the long axis of the southern molecular filament and the magnetic field. The magnetic field of this region is very consistent with the large scale field of the ρ Oph molecular cloud (Vrba et al. 1979). The formation of this filament therefore must be strongly coupled with the magnetic field. This tendency is the same for the ρ Oph A region, although the number of the observed sources are limited in this region.

In contrast, the magnetic field in the ρ Oph B region is systematically deviated from the general magnetic field by almost 90°. The molecular data suggest an anomaly of velocity field in the particular region. Therefore, the magnetic field might have been twisted by the kinetic motion of the filament.

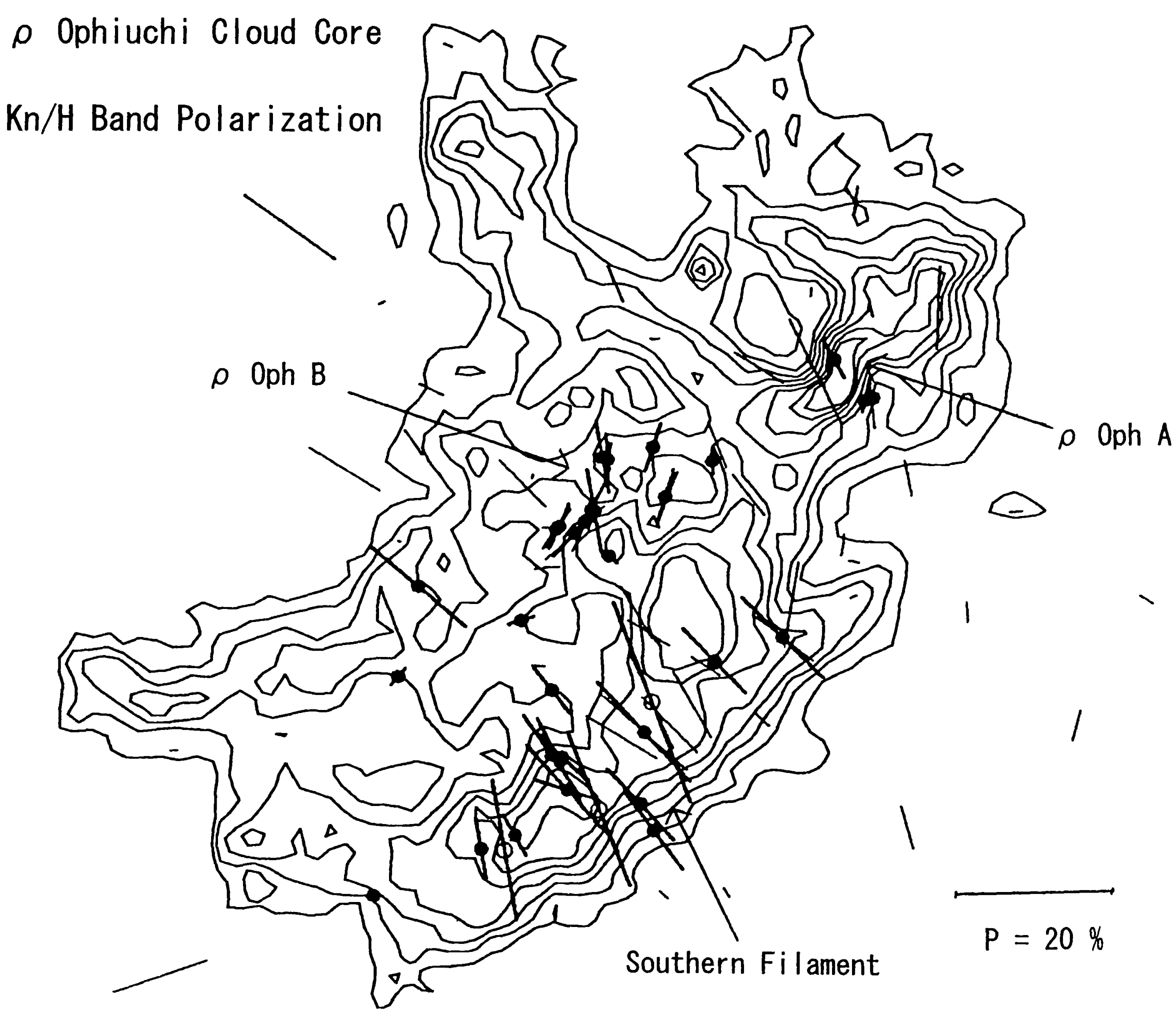

Figure 1. Kn/H band polarization map of the ρ Oph core, overlaid on the $C^{18}O$ map of the cloud core by Umemoto et al. (1995). Note that the polarization vectors represent the magnetic field direction projected on the sky. Thick vector with filled circle is K band data, while thick vector with open circle H band. Thin vector data are from Sato et al. (1988).

3.2. Does Near-Infrared Polarimetry Really Reveal the Magnetic Field in Dark Clouds? - Yes!

Very recently Goodman et al. (1995) have suggested that the near-infrared polarimetry is not useful in revealing the field inside the cloud because there is a decrease of polarization efficiency toward the denser region of the cloud. They infer that the NIR data represent only an integration of the outer part of the dark cloud. However, *as demonstrated by the sensitive spectro-polarimetric observations of Elias 16, a field star shining through one of the densest parts of the Taurus dark cloud, the polarization across the 3.1 μm ice-band feature DOES show a significant enhancement within this band feature, without any significant change of position angle* (Hough et al. 1988). This fact, not references in their paper, clearly and strongly suggests that the dust grains are well aligned within such a region where ice mantle grows, and therefore our near-infrared polarizations definitely trace at least the region where ices are well shielded from the external UV radiation. Such a region us by no means the outer part of the cloud and must be within the cloud where A_V is at least a few magnitudes.

3.3. Submillimeter Results

We have observed more the 30 young stellar objects, including 3 pre-T Tauri stars and 2 T Tauri stars (TTSs). Positive detections were made for NGC 1333 IRAS 4A and IRAS 16293-2422, while L1551 IRS 5 and HL Tau were only marginally detected. For GG Tau we measured a 2σ upper limit of 3.0%. In Fig. 2, we plot our 1.1 mm polarization vectors on the contour delineating the large disk/envelope structure. Detailed discussion on these results can be found in Tamura et al. (1995).

The observed 1 mm continuum emission from pre-TTSs is of thermal origin from dust is a disk-like structure of size several 1000 AU, while that for TTSs is thermal origin from the dust disk of size 100 AU. Therefore, 1 mm polarizations trace the magnetic field structure in the large scale disk (envelope) for pre-TSSs and that in the small scale disk for TTSs. Note that the electric vector of the thermal polarizations is perpendicular to the magnetic field direction projected on the sky.

In the three visible IRAS sources, we found a common relationship between the envelope magnetic field inferred from our 1 mm polarimetry and the envelope geometry: the envelope magnetic field is perpendicular to the major axis of the elongated envelope plane.

In contrast, the 1 mm polarization of HL Tau, a TTS, most likely represents the magnetic field in a transition zone between the disappearing envelope and disk. In this region, the magnetic field direction is parallel to the major axis of the elongated envelope.

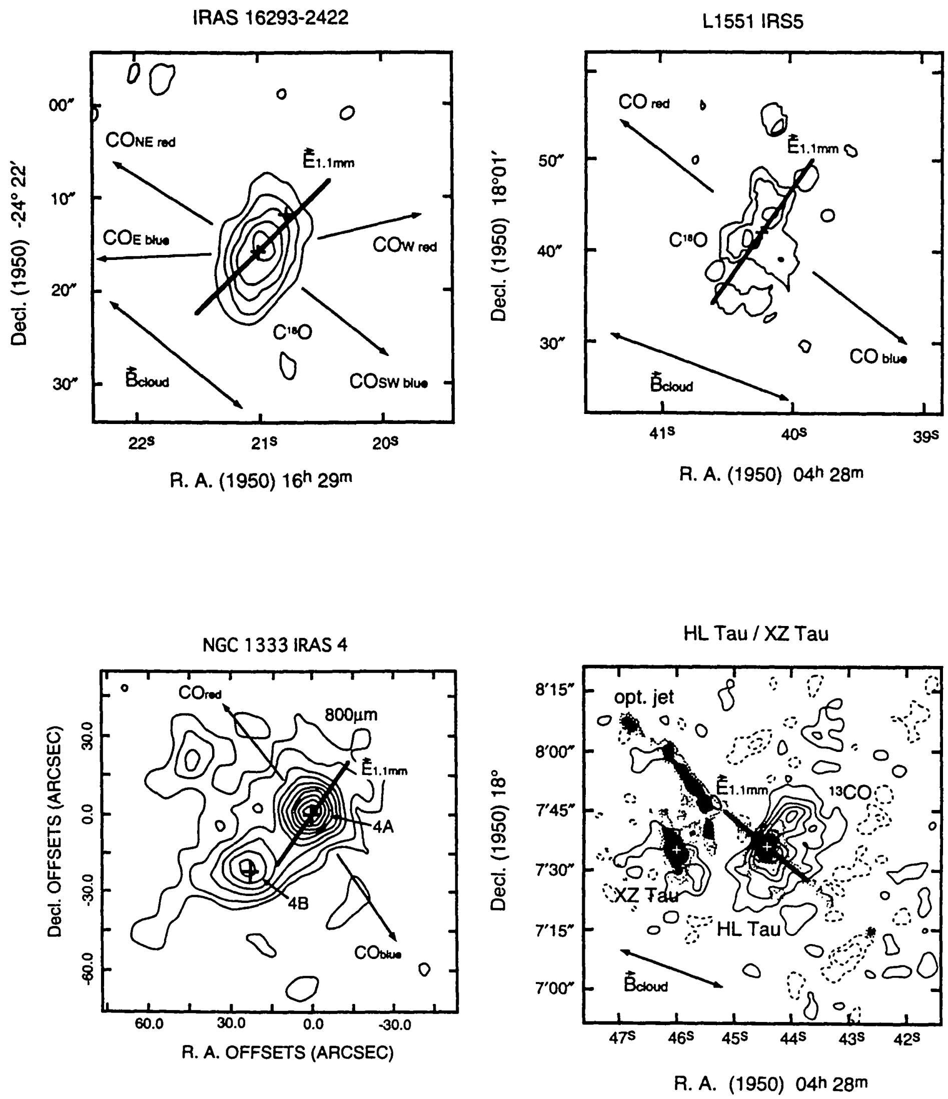

Figure 2. Relationship between 1 mm polarization vector (this work) and other circumstellar structure (large-scale disks, CO outflows and magnetic fields of embedding cloud).

We have not detected large 1 mm polarization in GG Tau that clearly has a small-scale disk.

A number of other (massive) YSOs are also polarized at a level of 3%. We believe that the observed polarizations infer the magnetic field structure in the cloud core associated with the YSOs. We have compared this magnetic field direction with various circumstellar environs including core elongation, outflow direction, parent cloud magnetic field direction, and Galactic Plane. We have found a correlation that the core magnetic field direction tends to be perpendicular to the parent cloud magnetic field direction. No significant correlations have been found with other features, however.

References

Goodman, A.A., Jones, T.J., Lada, E.A., & Myers, P.C. 1995, ApJ, 448, 748
Greene, T.P., & Young. E.T. 1992, ApJ, 395, 516
Hough, J.H. et al. 1988, MNRAS, 230, 107
Sato, S. et al. 1988, MNRAS, 230, 321
Tamura, M. et al. 1987, MNRAS, 224, 413
Tamura, M. et al. 1988, MNRAS, 231, 445
Vrba, F.J., Strom, S.E., & Strom, K.M. 1976, AJ, 81, 958

Part 6.

Grain Alignment