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Magnetic fields in cometary globules – I. CG 22

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ABSTRACT

We report first results from a programme to study magnetic fields in cometary globules (CGs). These are clouds near massive stars showing a head–tail morphology. Linear optical polarization measurements on stars seen projected on CG 22 in the Gum–Vela region are presented. A majority of the stars seen within the boundary of the cloud show a polarization of ~ 1 per cent with the electric field vector oriented parallel to the tail, whereas those outside the boundary either show small polarization with position angles parallel to the Galactic plane or show no polarization within the errors of our measurements. If the polarization is due to dust grains aligned by magnetic fields, our results imply that the field in CG 22 is parallel to its tail. A rough estimate of the field strength (~ 30 μG) indicates that it may be important for the dynamics of the cloud. These results support the idea that magnetic fields play a role in producing the structures seen in the tails of the CGs. We suggest that the alignment of the magnetic field could only have been caused by the same process that shaped the tails. We also comment on the implications of the polarization detected in the light from the star Wra 220, a T Tauri star believed to have formed in the head of CG 22.

Key words: polarization – stars: individual: Wra 220 – ISM: globules – ISM: individual: CG 22 – ISM: magnetic fields – ISM: structure.

1 INTRODUCTION

Massive stars have significant influence on the evolution of the ISM surrounding them. Systems of bright-rimmed clouds with head–tail morphology called the cometary globules (CGs) have been found near massive stars (Schneps, Ho & Barret 1980; Reipurth 1983; Zealey et al. 1983; Gyulbudagyan 1985; Sugitani, Fukui & Ogura 1991; Block 1992). Recent observations have established that individual systems of CGs are expanding away from central massive stars, possibly due to the *rocket effect* (Sridharan 1992a, b; Patel, Xie & Goldsmith 1993; Indrani & Sridharan 1994), and that star formation is going on in some heads (Pettersson 1991, and references therein; Sahu & Sahu 1992) at enhanced efficiencies (Bhatt 1993; Ramesh 1995). These results are in general agreement with the theory developed by Bertoldi (1989) and Bertoldi & McKee (1990) for clouds exposed to ionizing radiation. However, the role of magnetic fields in the evolution of these clouds and star formation in them has not been adequately addressed. The theory of Bertoldi & McKee treats magnetic fields only approximately, and observational efforts in this direction have been limited. Hodapp (1987) studied three globules believed to be associated with expanding interstellar shells, and found magnetic fields which he interpreted in terms of interaction with the shells. These globules, however, do not show clear head–tail morphology.

The Gum–Vela region harbours a sizeable population of CGs with their tails pointing away from a central region containing massive stars. Recent studies have established that this region is a good example of the effects of massive stars on their environments (Reipurth 1983; Sahu 1992; Sridharan 1992a, b). The CGs here show a variety of structures ranging from narrow filaments in the tails with aspect ratios as high as 10 (as in CG 22) to those that can hardly be called tails (as in CG 13). Tails which bend gradually (CG 1) or abruptly (CG 8) are also seen. The obvious question is what controls the morphology of the tails? Although the massive central star(s) can account for the presence and the overall radial orientation of the tails, the fine structure and the variety appear hard to explain. In particular, we noticed the following problem: from CO measurements we know that the linewidths, which presumably represent turbulent motion, are as large as the systematic velocity differences

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seen over the lengths of the tails (Sridharan 1992a). If, as suggested, the systematic velocity gradients stretched the clouds to form elongated structures, why has the velocity dispersion not caused the dispersal of the clouds in directions perpendicular to the tails? The CGs are not gravitationally bound, as evidenced by their masses derived from CO maps being significantly smaller than those required for virial equilibrium (Harju et al. 1990; Sridharan 1992b). Radiation and stellar winds from the central stars may quickly sweep material getting out of the head-shadow region, but this cannot explain structures narrower than the tail often seen in the CGs. With a velocity dispersion of ~ 1 km s^{-1} and typical widths of the filaments of ~ 1 arcmin the lifetime of these structures is $\sim 10^5$ yr, much shorter than the dynamical ages of the CGs of a few million years. This implies that either these structures are transient or there is a restraining agent which channels the flow in the tails. Magnetic fields aligned along the tails can confine gas and may also explain the bent tails.

One of the globules studied by Hodapp (1987), ESO 210-6A, is in the Gum–Vela region. Though not classified as a CG (Reipurth 1983), it shows a magnetic field pointing towards the central region of the system of CGs. The location of the globule is such that the direction to the central region is roughly parallel to the Galactic plane. Therefore it is not very clear whether the field detected by Hodapp is of general interstellar origin (parallel to the Galactic plane) or associated with the globule in particular.

Motivated by these questions, we have started a programme to study possible magnetic fields in the CGs. In this paper we report the detection of a magnetic field along the tail of CG 22 by studying polarization of starlight passing through it. This globule is the largest of the CGs; it shows streaky filaments well reproduced in CO maps (Sridharan 1992b), and has two condensations along its tail which may actually be separate objects (Sahu et al. 1988).

The observations are described in Section 2, and in Sections 3 and 4 we present the results and argue that the observed polarization is due to dust in CG 22. Section 5 discusses the results.

2 OBSERVATIONS

The observations were carried out with a fast star and sky chopping polarimeter coupled to the *f*/13 Cassegrain focus on the 1-m telescope at the Vainu Bappu Observatory, Kavalur on the night of 1995 March 6. A detailed description of the instrument and the method of data reduction may be found in Jain & Srinivasulu (1991). Briefly, the star and the neighbouring sky 2 arcmin away are observed alternately every 20 ms for 200 positions of the analyser. A function of the form $A + B \sin 2\theta + C \cos 2\theta$ is fitted to the (star − sky) difference data by least-squares to obtain the intensity, and the percentage and position angle of the linear polarization of the starlight. An unfiltered dry-ice-cooled R943-02 Hamamatsu photomultiplier tube was used for the measurements. 13 stars brighter than ~ 13 mag were observed with integration times of 5–10 min. An aperture of 30-arcsec diameter was used. The stars chosen were distributed over the head and immediately following tail region of CG 22; the two clumps further down the tail were not covered. The instrumental polarization was determined by observing unpolarized reference stars from Serkowski (1974), and was found to be 0.17 ± 0.026 per cent. The zero of position angle was determined by observing polarized standards from Hsu & Berger (1982). The results have been appropriately corrected for these effects.

3 RESULTS

The results of our observations are presented in Table 1. The magnitudes of the stars observed were obtained from the mean intensity. The photocathode response may be considered to approximate the Johnson *R* band. Stars 1 and 5 are identified to be SAO 199273 and 199269. Star 4 is identified with the Hα emission star Wra 220 [which is the same as PHα92; it has also been detected at 2.2, 50 and 100 μm (Reipurth 1983; Pettersson 1987; Sahu & Sahu 1992)]. We have used these three stars to calibrate the magnitude scale. The likely errors are ~ 0.5 mag. The stars b1, b2 and b3 from a separate survey (Bhatt 1995, unpublished) are in the Gum–Vela region $\approx 3°$ north-east of CG 22. The position angles listed are measured from north increasing towards east. The errors given are obtained from the least-squares fits. Fig. 1 shows the polarization vectors on an optical picture of CG 22 (from SERC '*J*' survey plates), with the CO contours (from Sridharan 1992b) also plotted. The lengths of the vectors are proportional to the percentage polarization, and the orientation is the same as that of the E field.

4 CAUSE OF THE POLARIZATION

We have plotted, in Fig. 2, the polarization position angle against the percentage polarization, for all the stars with detected polarization. The plot shows two clearly separated groups of stars, with low-polarization stars having position angle ~ 140, roughly parallel to the Galactic plane (group 1), and high-polarization stars showing position angles near 30, which is roughly the direction of the tail (group 2). We suggest that the origin of the polarization in the two groups is due to dust grains aligned by magnetic fields in the

Table 1. Summary of observations.

No.	mag (R)	%P	%ϵ_P	θ (°)	ϵ_θ (°)
1 (SAO199273)	9.0	0.54	0.10	139.1	10.5
2	9.7	0.29	0.14	16.2	
3	10.2	0.44	0.16	13.3	20.3
4 (Wra 220)	11.6	1.58	0.45	37.7	16.2
5 (SAO199269)	9.0	0.16	0.10	164.0	
6	10.5	1.16	0.19	4.4	9.4
7	8.4	0.36	0.08	145.1	12.8
8	10.0	0.83	0.13	30.3	9.1
9	10.5	0.96	0.19	16.6	11.6
10	9.2	0.54	0.13	25.1	13.6
11	10.6	0.84	0.29	52.8	19.8
12	10.7	0.43	0.24	59.6	
13	11.3	1.28	0.31	26.3	13.9
b1		0.25	0.06	112.7	6.8
b2		0.27	0.07	136.2	7.2
b3		0.56	0.10	115.9	4.8

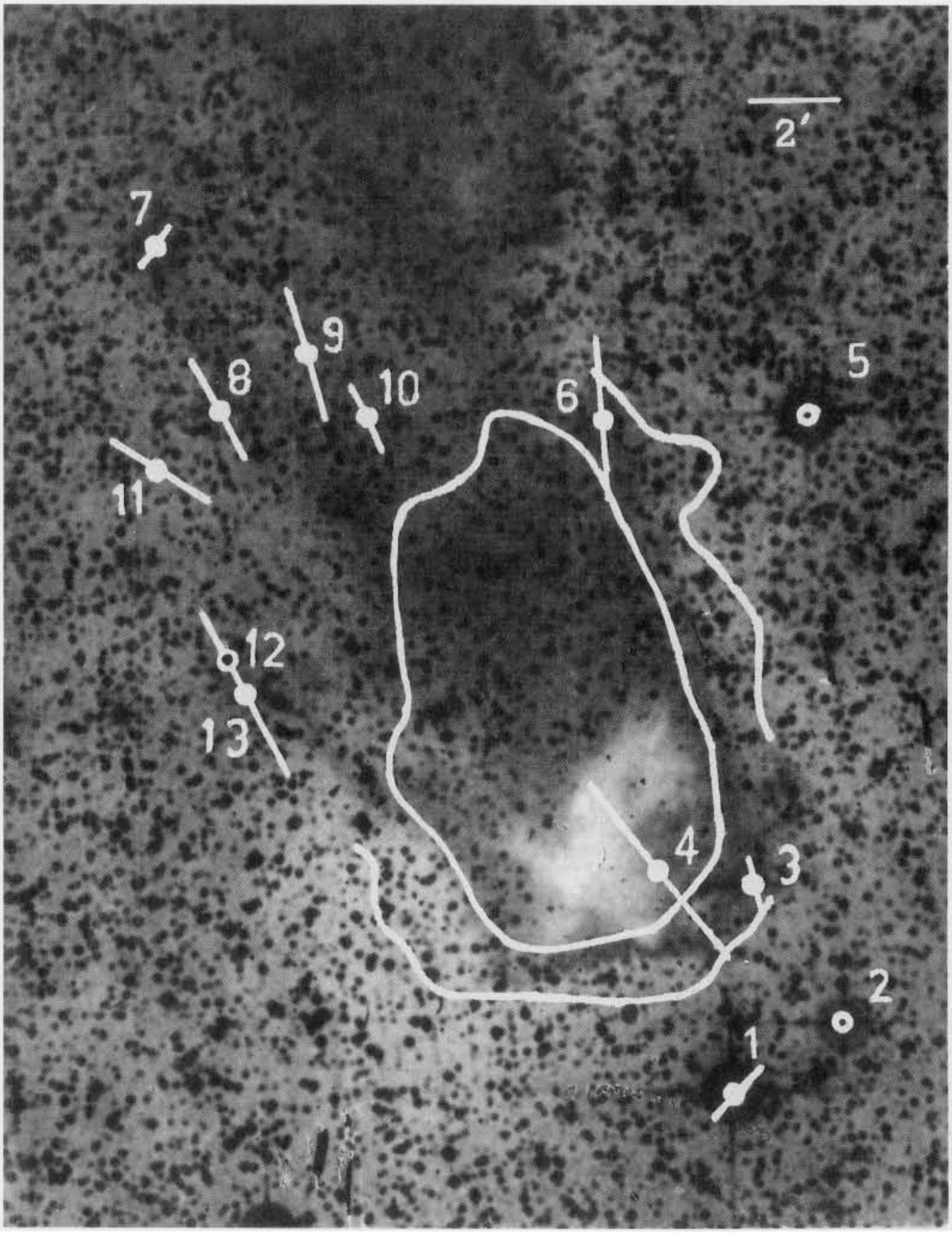

Figure 1. Polarization of stars seen projected on and near CG 22 (north is up and east is left). The lengths of the vectors are proportional to the percentage polarization, and the orientation is the same as that of the E field. Polarization vectors have been plotted only for those stars with detections better than or close to 3σ, and non-detections are marked by circles. CO contours from Sridharan (1992b) are also shown on the SERC survey picture. The inner contour corresponds to a $T_{\rm kin}$ of 10 K, and the outer contour represents the boundary. The cloud was not fully mapped on the northern side, where a condensation along the tail is seen.

general ISM and in CG 22 respectively. This is because the objects in the two groups also occupy different regions with respect to the boundary of the cloud as further discussed below.

From Fig. 1, we see that stars 1, 2 and 5, which are outside the cloud in projection, show polarization characteristics distinctly different from the other stars seen projected on the cloud. Polarization was not detected in light from stars 2 and 5 within our errors of measurement, and star 1 shows a small percentage polarization oriented very differently compared to the other stars. All the stars projected on the cloud, except star 12, have larger polarization with orientation parallel to the tail, and fall in group 2. Star 12 shows no polarization, even though it is within the cloud boundary. This may be due to this star being in the foreground of the cloud. From optical pictures, it is difficult to say whether stars 7 and 11 are within the cloud boundary or not. We note that the detection on star 11 is less than 3σ. However, the direction of polarization is similar to those of the other stars projected on the cloud. The detection on star 7 is better

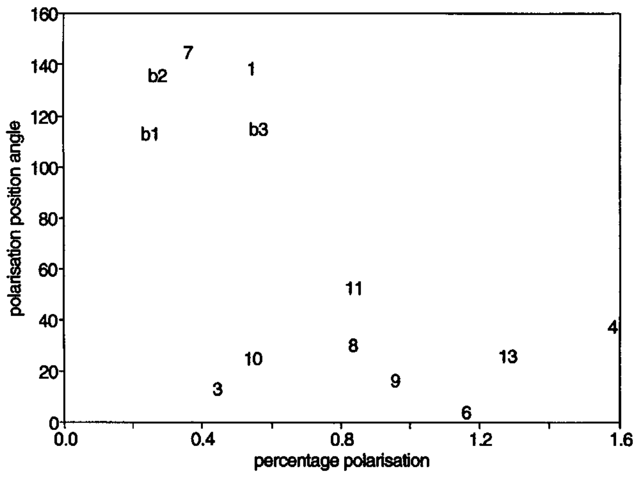

Figure 2. A plot of polarization position angle against percentage polarization.

than 4σ, and its direction is similar to that of star 1 which is outside the boundary. This direction is roughly parallel to that of the Galactic plane (145°). The direction of polarization caused by general interstellar dust being parallel to the Galactic plane (Mathewson & Ford 1970), we conclude that the polarization of the light from the stars 1 and 7 may be due to the general interstellar dust. The polarization position angles of stars b1, b2 and b3 further support this. Stars 2 and 5 show no polarization, presumably because they are closer than stars 1 and 7.

For stars in group 1, the amount of polarization is ~ 1 per cent, which implies a P/A_V ratio of ~ 1, using extinction data (~ 1 mag) from Sahu et al. (1988). This value is in agreement with measurements towards other clouds and in the general ISM where the polarization is believed to be caused by dust grains aligned by magnetic fields.

We recognize that the measurement of polarization of starlight in this region is complicated by the fact that the tail may be a reflection nebulosity and hence may contribute polarized light over the aperture used. We argue below that the observed polarization is unlikely to be due to this. The peak optical surface brightness anywhere over CG 22 is ~ 23.7 mag arcsec^{-2} in the 'J' band (from the SERC 'J' plates whose passband ranges from 395 to 540 nm; Sahu et al. 1988). If the optical nebulosity is due to reflection, it is likely to peak in the 'J' band. In the R band, which the photocathode approximates, the surface brightness is likely to be less. Over the aperture used (30-arcsec diameter) we estimate that the nebulosity will contribute light equivalent to 16.6 mag. If this light is 100 per cent polarized, we estimate that it can result in 1 per cent polarization for stars fainter than 12.4 mag, assuming no chopping. The star/sky chopping will remove much of the light due to the optical nebulosity; only brightness gradients over 2-arcmin angular scales will contribute, and this will be much less. As the faintest star on which we have detected polarization is 11.6 mag (star 4), we conclude that our polarization measurements are not contaminated by contribution from possible reflected light. The fact that star 12 showed no detectable polarization supports this. Further, the observed orientation of the polarization vectors, if due to reflection, indicates a direction for the source of light towards a region where there are no bright stars.

From the above arguments we conclude that the polarization of light from stars seen projected on CG 22 is due to selective extinction by dust grains aligned by magnetic fields in this cloud.

5 DISCUSSION

5.1 Magnetic field

If the polarization is due to non-spherical dust grains aligned by magnetic field, through, for example, the Davis–Greenstein mechanism, the polarization position angles also represent the orientation of the magnetic field projected on the sky. Orientation of dust grains by flow along the tail will cause polarization perpendicular to what is seen. Assuming alignment by magnetic field, our results imply that the plane of the sky component of the magnetic field in CG 22 is oriented parallel to its tail. The mean value of the position angles is 22°.5, with an rms dispersion of 5° (1σ). The tail itself shows a total variation in position angle of $\sim 30°$. There is an indication of the B-field orientation following this variation, but more accurate data are needed to confirm this. It appears reasonable to conclude that the magnetic field is quite tightly aligned to the tail in three dimensions. Similar observations towards ESO 210-6A, a globule with wind-blown appearance in the Gum–Vela region, made in the near IR by Hodapp (1987) have resulted in the detection of a magnetic field pointing towards the central region. As already mentioned in the Introduction, in the case of ESO 210-6A this field could also be of general interstellar origin, whereas for CG 22 our data establish the presence of a field aligned to the tail. In two other globules Hodapp has found bent field structure near the head, which is seen neither in ESO 210-6A nor CG 22, possibly because of the limited number of stars observed. Polarization data on more CGs along with better coverage will be useful in establishing these conclusions.

As mentioned previously, the P/A_V ratio is similar to that in the general ISM. Following Greenberg (1978; see also Whittet 1992), the required magnetic field strength is given by

$$B^2 \sim 0.5 a n_{\rm H} T_{\rm d} T_{\rm g}^{1/2}, \tag{1}$$

where a is the average grain size in μm, $T_{\rm d}$ and $T_{\rm g}$ are the dust and gas temperatures, and $n_{\rm H}$ is the hydrogen gas number density. Using CO data from Sridharan (1992b) and *IRAS* data from Sahu et al. (1988), we obtain values for $n_{\rm H}$, $T_{\rm g}$ and $T_{\rm d}$ to be ~ 200 cm^{-3}, 10 and 30 K in the outer parts of the cloud. Assuming $a = 0.1$ μm gives a value of 30 μG for B. The values of the parameters going into this estimate are only approximate, and there is uncertainty about the quantitative validity of the Davis–Greenstein mechanism. We stress that this field strength is a rough estimate and is intended only to give an idea of the kind of fields involved. The energy density in such a magnetic field is $B^2/8\pi \sim 3 \times 10^{-11}$ erg cm^{-3}. From the CO linewidths of ~ 1 km s^{-1}, the energy density in gas motion is $\sim 10^{-11}$ erg cm^{-3}. This suggests that the magnetic field may be important in deciding the gas motions. In other words, it could be playing a role in confining the gas in the tail, as suspected.

5.2 Polarization of starlight from Wra 220

The large polarization measured on star 4, which is believed to be a T Tauri star formed in CG 22, is interesting. Light from such young stars may have intrinsic polarization due to scattering by circumstellar structures like discs. The polarization vector in such cases is known to be parallel to the disc (Bastien 1987, and references therein). The orientation of the polarization for this star is similar to the other stars, and the disc, if present, is oriented parallel to the magnetic field in the tail. On the other hand, current theories of star formation suggest the formation of flattened circumstellar structures perpendicular to the magnetic field. This inconsistency can be reconciled if the field in the core is unrelated to the field in the tail. A similar conclusion was reached by Hodapp for the globules ESO 210-6A and L810.

If the polarization is not due to such structures, it implies dust alignment deep inside the cloud where the star is presumably embedded. From CO data, $n_{\rm H}$ is $\sim 10^3\ \mathrm{cm}^{-3}$, indicating a magnetic field strength of $\sim 70\ \mu$G. Further observations to distinguish between these two cases will be very useful because of the implications for the origin of the aligned magnetic fields in the CGs. In the second case, any mechanism seeking to explain the geometry of the field should be able to produce aligned fields deep inside the cloud.

5.3 Origin of the field

We make some preliminary remarks about the possible origin of the aligned magnetic field. First, we assume that the magnetic fields in general are aligned to the tails in all CGs, which is consistent with our data on CG 22 and Hodapp's observations. This needs to be established but seems very likely. Clearly, such a field could not have existed in the original molecular cloud from which the CGs formed. This is because, given the radial distribution of the CG tails, a pre-existing magnetic field would have to be already pointing radially in the molecular cloud, which appears far-fetched. It is more likely that processes that formed the CGs were also responsible for creating the aligned magnetic field, possibly from a pre-existing randomly oriented seed field. Tentatively, radiation pressure on charged dust grains could have resulted in these grains being accelerated along the tail stretching any pre-existing magnetic fields along the tail. Ionized gas flow along the tails will also lead to the same result. Dust grains in H II regions can have charges of $\sim 100e^-$, and the initial magnetic fields may not have been strong enough to prevent radiation pressure from pushing the grains. The theory of Bertoldi (1989) treats only special cases where the magnetic field is oriented either parallel or perpendicular to the symmetry axis. In both cases, their post implosion clouds have magnetic fields oriented in the same way as the initial cloud. In this picture, our results would imply an unlikely situation where magnetic fields parallel to the future tails are already present in pre-implosion clouds. More theoretical work for quantitative comparison with observations will be useful.

At this point we would like to comment on a suggestion by Scarrott et al. (1992) of a possible large-scale magnetic field in this region parallel to the Galactic plane which influences star formation, leading to various aligned structures. The direction of the field they have assumed is from Hodapp's measurements towards ESO 210-6A. The magnetic field direction inferred from our data is $\sim 68°$ away from that in ESO 210-6A, and would appear inconsistent with this picture. However, the detected fields may be unrelated to those in the cores of individual globules (Hodapp 1987), whose orientations need to be measured to test Scarrott et al.'s suggestion.

6 SUMMARY

We have presented results of linear optical polarization measurements on stars seen projected on CG 22 in the Gum–Vela region. For stars within its boundary the cloud causes a polarization of ~ 1 per cent with the electric field vector oriented parallel to the tail, whereas those outside the boundary show either small polarization with position angle parallel to the Galactic plane or no polarization within the errors of our measurements. If the polarization is due to non-spherical dust grains aligned by magnetic fields, the implied field in CG 22 is aligned parallel to its tail. A rough estimate of the field strength indicates that it may be dynamically important. These results support the idea that magnetic fields play a role in shaping the structures seen in the tails of the CGs. We suggest that the alignment could only have been caused by the same processes responsible for the formation of the tails.

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