Magnetic fields and dust in vicinities of globules

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Star formation and globules

Small rather isolated dark clouds called globules are known to be the places of formation of low-mass stars.

The star-formation process is still not well understood in many important details, in particular, e.g., some globules contain protostellar objects, while many others have starless cores.

The star formation is strongly affected by the magnetic fields, cloud rotation, etc. Modeling is difficult and hence only slowly improving. It still needs more detailed observational data concerning both the internal regions of the clouds and their outer regions and environments.

We discuss approaches based on analysis of polarization of background radiation which are used to study the magnetic fields and dust in close vicinities of globules by us and other groups.
Interstellar radiation, dust, and magnetic fields are known to be tightly related in the general ISM and globules. It gives the following observational approaches utilized by us and others for globules:

1) visual or near-IR polarization mapping that gives the direction, topology (and maybe strength via the C-F method) of the magnetic fields;

2) multi-wavelength (visual, IR & sub-mm) polarization mapping providing information on magnetic field changes in different density regions;

3) wavelength dependence of polarization and extinction of background radiation informing us about the mean properties of dust grains.

The results must be supplemented with other data available:

- globule maps (and spectra) in different molecular lines,
- dust extinction maps of the globule region,
- dust emission maps (both large and small-scale ones),
- information on large-scale distribution of material and magnetic fields in the globule direction,
- and so on.
In all 3 approaches (excluding submm polarization) we observe:

hardly outer molecular layers of globules,
but mainly the neutral halo of globules and sometimes even regions outside it!

It is difficult to study the halos and generally transition H$_2$-HI regions, and just a few studies have been done (e.g., Wannier+, 1999; Bensch, 2006; Goldsmith+, 2007; Launhardt+, 2013; Stanimirovic+, 2014).

What is known about the halos:

• extinction $A_V \approx 0.5 – 1$ mag,
  $n \approx 30 – 50$ cm$^{-3}$,
  $T \approx 30 – 60$ K;
• halo size is about 2-3 times larger than the visual one;
• inhomogeneous structure and complicated shape;
• etc.

As an example, HI 21 cm emission map of the halo around B5 globule shown by white contours (from Wannier+, 1999).
The main difficulty of the approaches is an unclear contribution of halo as it is very difficult (if even possible) to separate contributions of:

1. foreground diffuse material;
2. globule halo;
3. other cloudy material in the local ISM ($d < 500$ pc);
4. background material ($d > 500$ pc).

But when one considers a close ($d < 150$ pc), high galactic latitude globule, the contribution of points 1 and 4 is as small as possible.

Contemporary 3D maps of material distribution in LISM are becoming more reliable (e.g., Lallement+, 2014; Puspitarini+, 2014), but the point 3 is still a problem.

An example is the globule CB66 observed by us at Giravali Obs.
Complications because of:
- effects of a very close B0 star ζ Oph \( E(B-V) = 0.32 \) mag for \( d = 112 \) pc, while \( E^\infty(B-V) = 0.55 \) mag in this direction;
- 2 layers of material: before \( (d < 120 \) pc, Loop I interface?) and behind \( (d > 200 \) pc) Sco OB2 association (see, e.g., Wolleben+, 2010; Lallemont+, 2014).

This may be the reason of wide distributions of P.A.

Other data:

<table>
<thead>
<tr>
<th>P.A.</th>
<th>d, pc</th>
<th>objects &amp; regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 – 70</td>
<td>17-28</td>
<td>4 stars in the local ISM (Frisch+, 2012)</td>
</tr>
<tr>
<td>126</td>
<td>112</td>
<td>diffuse ISM towards ζ Oph (McDavid, 2000)</td>
</tr>
<tr>
<td>30 – 140</td>
<td>&lt;200</td>
<td>40 stars in a 7° circle (Heiles, 2000; Santos+, 2011)</td>
</tr>
<tr>
<td>50 – 150</td>
<td>&lt;300</td>
<td>many stars in the Loop I interface (Santos+, 2011)</td>
</tr>
<tr>
<td>~80</td>
<td>?</td>
<td>1 sq. deg. field of Planck data (Planck collab., 2014)</td>
</tr>
<tr>
<td>50 – 100</td>
<td>&gt;110</td>
<td>stars around L204 cloud chain (McCutcheon+, 1986)</td>
</tr>
</tbody>
</table>

So, the contribution of CB66 halo is not clear ...
Many globules have been mapped in visual and near-IR polarization:
starting with the pioneer works of the 1980s (e.g., Johes+, 1984; Joshi+, 1985; Seki+, 1987),
with a systematic study by Clemens’ group (Clemens, Kane, 1994; Clemens, 2012),
and essential contributions of several Indian groups (e.g., Sen+, 2000; Bhatt+, 2004; Eswaraiah+,
2013), a Brazilian group (e.g., Rodrigues+, 2013) and others.

However, good maps (more than ~30 P-vectors) were obtained only for about 20 globules
(many, but not enough for good statistics).
For most globules, the surrounding magnetic fields show a regular behavior, while for ~20%
globules these fields demonstrate a more complicated or irregular behavior (e.g.,
Rodrigues+, 2013). The reason of this is not yet clear.

Other main findings are well summarized by Hua-bai Li+ (2014, P&P VI):
• competition between gravity and turbulence shapes the clouds and cores to be elongated
  either parallel or perpendicular to the magnetic field;
• the field in the cloud “remembers” the direction of the Galactic field;
• protostellar disk and outflows seem to be not aligned by the magnetic field,
  and so on…
The ability of the approach is illustrated by our observations of a quickly rotating globule CB67 made at Giravali Obs. in 2013.

Fig. 3. Polarization of stars in the region of CB67. The dotted lines show emission in the $^{13}$CO line, the solid lines emission at 850 μm. The dashed line confines the area observed in submm range (Visser+, 2001).

We find that elongation (X) and rotation moment (J) of CB67 are oriented rather perpendicular to the magnetic field, which is unusual for Bok globules and is difficult to be explained from the theoretical point of view (Prokopjeva+, 2014).
Mapping at different wavelengths (example of CB68)

Comparison of polarization maps obtained in visual, near-IR and sub-mm regions is just being developed (e.g., Reissl+, 2014).

Usually, polarization in near-IR appears to follow the visual polarization (see, e.g., Magalhaes, 2012; Cashman, Clemens, 2014), while sub-mm polarization can show a rather complicated topology (see, e.g., Hull+, 2013).

Fig. 5. Polarization in the region of CB68:
the left panel presents our data in visual obtained at Giravali Obs.;
the central panel shows the map in $^{12}$CO (3-2) line and polarization in the H band (Bertrang+, 2014);
the right panel does the polarization in submm region obtained at SCUBA/JCMT (Vallee+, 2003).
Wavelength dependences of polarization of background stars have been obtained for several dark clouds (e.g., Vrba+, 1993) and only for a couple of globules as it is not simple.

For example, in the recent excellent paper of Eswaraiah+ (2013) mainly VRI polarization data were obtained which is obviously not sufficient for an analysis of $P(\lambda)$ when $\lambda_{\text{max}} \sim 0.6$ μm.

Most interesting data were obtained for B5 globule (Joshi+, 1985; Bhatt, 1986), but they were not supplemented by photometric and spectral data.

Generally, one expects that in globules the mean size of dust grains $\langle a \rangle \sim \lambda_{\text{max}}$ should be larger than in diffuse ISM, but the known mechanisms of grain growth may not work in such small clouds.

Note that we do not deal with rather dense regions and hence can be less pessimistic than Goodman (1996) as concern using the starlight polarization as a dust diagnostic tool.
We performed (U)BVRI observations of over 30 field stars and stars as close to the B5 center as possible at 2.6-m and 1.25-m telescopes of Crimea Obs.

They strongly increased the number and accuracy of $\lambda_{\text{max}}$ estimates.

Data for several stars projected on the B5 layers with $A_V \approx 2-3$ mag:

<table>
<thead>
<tr>
<th>Bhatt (1986)</th>
<th>this work</th>
</tr>
</thead>
<tbody>
<tr>
<td>star</td>
<td>$\lambda_{\text{max}}, \mu$m</td>
</tr>
<tr>
<td>Jo1</td>
<td>0.79 ± 0.06</td>
</tr>
<tr>
<td>Jo2</td>
<td>0.85 ± 0.08</td>
</tr>
<tr>
<td>Jo6</td>
<td>0.80 ± 0.11</td>
</tr>
<tr>
<td>Jo16</td>
<td>1.11 ± 0.29</td>
</tr>
</tbody>
</table>

and so on.

Fig.6. Wavelength dependence of polarization of some stars close to Barnard 5
Our additional spectral and multicolor photometric observations performed at different observatories as well as data of recent sky surveys allowed us to exclude foreground and too distant stars.

Fig. 7 All stars observed in vicinities of B5 globule.
Red lines are contours for $A_V = 3$ and $5$ mag from 2MASS-based extinction map (Ridge+, 2006)
Dashed line is contour of the peak $^{12}\text{CO}$ temperature (cf. with the HI emission map presented earlier).

We find a clear relation between $\lambda_{\text{max}}$ and $A_V$:

$$\lambda_{\text{max}} \sim 0.6 \ \mu\text{m for } A_V \sim 1\text{-}2 \ \text{mag} \ \text{and} \ \lambda_{\text{max}} \sim 0.8 \ \mu\text{m for } A_V \sim 3 \ \text{mag}.$$ 

We believe that it is a much more reliable indicator of the larger mean sizes of dust particles in globules than those having been considered (e.g., Foster+, 2013).
Conclusions

To our opinion, there are still some interesting tasks of polarimetric studies of globule vicinities when additional observational data are available.

Just a few of such tasks:

- not everything is clear as concern the magnetic field topology around star-forming and quiescent globules;

- more statistics is required, e.g., to understand relation of the magnetic field, rotation and shape of globules;

- connection of topologies of the submm thermal radiation polarization and of near-IR/visual polarization due to extinction by dust requires a further study;

- the question of the mean size of dust grains in globules is still actual, and so on…