Watching the Interstellar Medium Move

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Bart Bok and the “Dark Nebulae”

“They are no good, and only a damn fool would be bothered by such a thing. A sensible person does not get involved with the dark nebulae but steers to the clear parts in between.”

--Pieter van Rhijn, Bok’s Thesis Advisor

Taurus Dark Cloud Complex
100 \( \mu \text{m} \) ISSA image

3 pc
Taurus: Star Counting

Arce & Goodman 1998

Star counting

Declination [deg, 1950]

$A_v$ [mag]
Taurus: Star Counting, Color Excess of Stars

Arce & Goodman 1998

- Star counting
- Stars with spectral classification
Taurus: All Methods of Measuring Extinction

Schlegel, Finkbeiner & Davis 1998

- COBE+ISSA

Arce & Goodman 1998

- Star counting
- Stars with spectral classification
- ISSA in star pixel
- ISSA (cut width average)
- ISSA (cut width average)
- Average color excess

Declination [deg, 1950]

$A_V$ [mag]

Declination [deg, 1950]
“With the increased angular resolution to be provided by paraboloid antennas now under construction, and with continued emphasis on the improvement of electronic equipment, 21 cm research promises to provide increasingly useful information on the cloud structure of the interstellar medium. By continuing our efforts to blend optical and radio studies of the interstellar medium into one whole, we have real hope of greatly advancing our knowledge of the interstellar medium in years to come.”

Adding a Third Dimension

Spectral Line Observations

Mountain Range

No loss of information

Loss of 1 dimension
SNR
Outflows
MHD Waves
Dense Cores/Bok Globules
Infall
Thermal Motions
Turbulence
H II Regions
SNR
Watching the ISM Move

- **W3: Massive Star-Forming Region**
  - velocity information explains magnetic field geometry & star formation

- **Ursa Major: High-Latitude Cloud**
  - velocity analysis shows “dripping” & impact

- **Dense Cores**
  - velocity dimension reveals “coherence”

- **Spectral Correlation Function**
  - should lead to better simulations & more
W3

$^{13}$CO Integrated Intensity

Dust Thermal Emission

$^{13}$CO Channel Maps

-39 to -31 km/sec

-49 to -41 km/sec

Kannappan & Goodman 1998; Dowell 1998
The Origin and Evolution of High-Latitude Clouds

Pound & Goodman 1997

Ursa Major HLC Complex
High-latitude Clouds

- “High-latitude” = very nearby ($D_{\text{UMA}} \sim 100$ pc)
- ~No star formation$^1$
- Energy distribution very different than star-forming regions

<table>
<thead>
<tr>
<th>High Latitude Cloud$^2$</th>
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<tbody>
<tr>
<td>Gravitational $&lt;&lt;$ Magnetic</td>
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<tr>
<td>Kinetic</td>
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<table>
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<tr>
<th>Star-Forming Cloud$^3$</th>
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(1) Magnani et al. 1996; (2) Myers, Goodman, Güsten & Heiles 1995; (3) Myers & Goodman 1988
The Velocity Field in **Ursa Major**

*Pound & Goodman 1997*
Hat Creek H I Data

\Delta \nu \text{ and } v_{\text{LSR}} \text{ Gradients}

- Latitude [deg]
- Longitude [deg]

- \Delta \nu
- v_{\text{LSR}}
In General...

\[ \Delta v_{\text{tan}} \]

\[ \Delta v_{\text{rad}} \]

Line width primarily tangential

Line width primarily radial

In Ursa Major

\[ \Delta v_{z,\text{obs}} \]

Implication:

\[ \Delta v_{\text{tan}} \gg \Delta v_{\text{rad}} \]

Implication:

\[ \Delta v_{\text{tan}} \ll \Delta v_{\text{rad}} \]


\textbf{CO Bluedshifted w.r.t. HI in both filaments, in arc-like pattern}
Red

Blue

Observed in Ursa Major

CO blueshifted w.r.t H I Shell
Implications of Ursa Major Study

• Many HLC’s may be related to “supershell” structures; some shells harder to identify than NCP Loop.

• (Commonly observed) velocity offsets between atomic and molecular gas may be due to impacts, followed by conservation of momentum. Use this as a clue in other cases.
Bok and his Globules

“In recent years several authors have drawn attention to the possibility of the formation of stars from condensations in the interstellar medium (Spitzer 1941; Whipple 1946).”

Bok and his Globules

“The globules are interesting objects… Every one of them merits further careful study with the largest available reflecting telescopes.”

1990: "Bart Bok Was Correct!"

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STAR FORMATION IN SMALL GLOBULES: BART BOK WAS CORRECT!

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Received 1990 August 15; accepted 1990 October 4

ABSTRACT

We have probed a large sample of optically selected, small molecular clouds (Bok globules) using IRAS co-added images to search for associated young stellar objects. The IRAS images were examined for point sources located within the boundaries of the optical and infrared extents of 248 clouds. A total of 57 of the globules (23% of the sample) show evidence for associated point sources. From a comparison of the 12 and 25 μm fluxes of these objects, we find a distribution of spectral indices consistent with the presence of circumstellar dust. Similar analysis of other point sources within the IRAS images, but far from the globule boundaries, shows only normal stellar spectral indices. All young stars more massive than 0.7 M⊙ were likely found. However, extrapolation of a Miller-Scalo initial mass function to the hydrogen-burning limit indicates that only about 20% of the total number of stars were found. It is therefore likely that almost every Bok globule harbors a young star. The inferred star formation efficiency is about 6% again based on the Miller-Scalo initial mass function. Interestingly, this is the best test in 43 years of the conjecture made by Bart Bok that dust globules could represent the earliest stage of star formation. We are pleased to report that his conjecture was correct.

Motions Of, In and Around Dense Cloud Cores

- Rotation
  - $\beta \sim 0.04$; enough to matter but not to fragment

- Velocity Coherence
  - Cores as “Islands of Calm in a Turbulent Sea”

- Bulk motion
  - Infall: see Ho, Lada, Keto, Myers, Williams, Wilner, Zhang...
  - Outflow: see Arce, Lada, Raymond...
Coherent Cores: “Islands of Calm in a Turbulent Sea”

"Rolling Waves" by KanO Tsunenobu © The Idemitsu Museum of Arts.
Hint #1: Independent Core Rotation

Goodman, Benson, Fuller & Myers 1993
Hint #2: Constant Line Width in Cores?
Types of Line width-Size Relations

Ensemble of Clouds

FWHM of Various Tracers Shown

Type 1: “Larson’s Law”

\[ \Delta v \sim R^{0.5} \]

Non-thermal Line Width

Observed Size

Gives overall state of ISM\textendash magnetic virial equilibrium.
See Larson 1981; Myers & Goodman 1988 for examples.
Types of Line width-Size Relations

"Type 3:" Single Cloud Observed in Multiple Tracers

Gives pressure structure of an individual cloud.
Types of Line width-Size Relations

“Type 3:” Single Cloud Observed in Multiple Tracers
Types of Line width-Size Relations

“Type 4:” Single Cloud Observed in a Single Tracer

Gives information on power spectrum of velocity fluctuations.
An Example of the (Original) Evidence for Coherence

Type 4 Line width-“Size” Relations

\[ \Delta v_{NT} = (1.0 \pm 0.2)R^{0.27 \pm 0.08} \]

\[ \Delta v_{NT} = (0.30 \pm 0.09)R^{0.12 \pm 0.08} \]
The (Newer) Evidence for Coherence

Type 4 slope appears to decrease with density, as predicted.
Coherent Dense Core

"Velocity Coherent" Core

"Chaff"...

~0.1 pc (in Taurus)
“Coherence” in Spatial Distribution of Stars

Surface Density of Stellar Companions (Taurus)

Parameterized Line Width-Size Relation

\[ \log \Sigma_c(\theta) \text{[stars/sq. deg]} \]

\[ \log \theta \text{[deg]} \]

\[ \sigma_\perp \text{[km s}^{-1}] \]

Size [pc]

Larson 1995; see also Gomez et al. 1993; Simon 1997

Goodman et al. 1998.
The Cause of Coherence?

Most likely suspect:
- Loss of magnetic support due to reduced ionization fraction in core. (Scale gives clues.)

Interesting question raised:
- What causes residual non-thermal line width?

No ambipolar diffusion yet...
Learning More from “Too Much” Data

The diagram shows the increase in the product of signal-to-noise ratio (S/N) and the number of channels over time. The y-axis represents the product of (S/N) and N pixels, while the x-axis represents the year. The trend lines show a significant increase from 1950 to 2000, indicating a substantial improvement in the ability to learn from data.
The Spectral Correlation Function

Figure from Falgarone et al. 1994 Simulation
Goals of “SCF” Project

• Develop a “sharp tool” for statistical analysis of ISM, using as much data of a data cube as possible

• Compare information from this tool with other tools (e.g. CLUMPFIND, GAUSSCLUMPS, ACF, Wavelets), applied to same cubes

• Use best suite of tools to compare “real” & “simulated” ISM

• Adjust simulations to match, understanding physical inputs
How the SCF Works

• Measures similarity of neighboring spectra within a specified “beam” size
  – lag & scaling adjustable
  – signal-to-noise equalized

A “Real” Molecular Cloud

IRAM Key Project Data
Initial Comparisons using the SCF

L1512 (Real Cloud)  "Matching?" Turbulence Simulation

IRAM Key Project Data  Falgarone et al. 1994
Initial Comparisons using the SCF

L1512 (Real Cloud)  Better? MHD Simulation

IRAM Key Project Data  Gammie, Ostriker & Stone 1998
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Extra slides follow...
Optical View of W3 Region
“Go no further than $A_V \sim 1.3$ mag.”

Arce et al. 1998

Background to Cold Dark Cloud

Background to General ISM

Magnetic Fields
“Star and Planet Formation”

- Giant Molecular Clouds
- "Cores" and Outflows
- Solar System Formation
- Jets and Disks