Dendrogram analysis of the first CARMA Large Area Star formation Survey regions

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June 8, 2013
CARMA Symposium

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**Big Picture**

How do dense cores form and evolve to form stars?
- Turbulence, magnetic fields, self-gravity, heating, chemistry

**What We Know and Don’t Know about Turbulence**
- Observe supersonic gas in GMCs
- Observe turbulent scaling laws
- What are the turbulence drivers?
- Can we detect predicted signatures of turbulence driven core formation?

**Observational Experiment for this Talk**
- Identify dense gas structures $N_2H^+(1-0), n > 10^5 \text{ cm}^{-3}$
- Characterize their velocity field

**Hypothesis**
- Expect differences in turbulent properties
  - NGC 1333: many young protostars driving outflows
  - Barnard 1: mix; SW= filamentary without protostars
Not an issue of choosing the CORRECT object identification method, but choosing the MOST APPROPRIATE method.

Observational Experiment for this Talk

- Identify dense gas structures ($n > 10^5 \text{ cm}^{-3}$)
- Characterize their velocity field
Object Identification Methods

Cloudprops (best for sparse fields) vs. Dendrograms (best for dense/blended fields)

Molecular Cloud structure is mostly hierarchical ... dendrograms avoid small-scale segmentation and naturally capture large-scales in addition to the small-scales
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Capturing Large and Small Scales with Dendrogram Approach

Moment Zero Maps of Leaves and Branches

Facilitates an investigation of the turbulent properties of dense gas at different scales in a way that clumpfind-like segmentation would not allow.
Dendrogram Implementation: A New Clustering Method

Traditional: binary dendrogram

New: Non-binary dendrogram

Forcing binary clustering results in “phantom” branching structure where > 2 structures should merge considering the noise limitations of real data.
Results: Non-Binary Dendrogram of NGC 1333 N$_2$H$^+$ (1-0)

- Represents the observable hierarchy of emission within the limits of the noise
- Meaningful list of structures not polluted by phantom branching
Results: Non-Binary Dendrogram of NGC 1333 N$_2$H$^+$ (1-0)

We evaluated the size and kinematics of each identified gas structure.

How do larger-scale gas structures compare to smaller-scale structures?

Turbulence across different spatial scales within a single cloud... across different clouds at different stages of evolution?
Results: Non-Binary Dendrogram of NGC 1333 N$_2$H$^+$ (1-0)

Fitted Line Dispersion Maps

<table>
<thead>
<tr>
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<th>33</th>
<th>12</th>
<th>51</th>
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<td>42</td>
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<td>11</td>
<td>59</td>
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How do larger-scale gas structures compare to smaller-scale structures?

Turbulence ... across different spatial scales within a single cloud ... across different clouds at different stages of evolution?
Results: Line Dispersion vs. Size in NGC 1333 Gas Structures

Capturing mean internal turbulence... at 11 K and 25 K
Results: Non-Binary Dendrogram Structure of Barnard 1 \( \text{N}_2\text{H}^+ (1-0) \)

*Spitzer* IRAC + \( \text{N}_2\text{H}^+ \) outline

black = nearby protostellar outflows
red = further from outflow activity
Results: Cross-Cloud Comparison

Barnard 1 vs. NGC 1333

- H$_2$ thermal dispersion
- N$_2$H$^+$ thermal dispersion
  - at 9 K and 12 K

- H$_2$ thermal dispersion
- N$_2$H$^+$ thermal dispersion
  - at 11 K and 25 K
Results: Cross-Cloud Comparison

Barnard 1 vs. NGC 1333

- Observe supersonic turbulence at ~0.01 – 0.5 pc scales near active young stars
- Indication that outflows are an important turbulent driver of the dense gas at these scales
Results: Cross-Cloud Comparison

Barnard 1 vs. NGC 1333

- Observe subsonic turbulence in filamentary regions yet to form young, active stars
- ... expected if these dense gas filaments formed from supersonic turbulence
- Next step to probe even larger scales and make connection to lower density gas
Summary

- Dendrograms used to decompose dense gas emission and explore kinematics of structures in CLASSy clouds
- Created statistically meaningful sample of gas structures with new non-binary clustering version of dendrograms
- Compared turbulent linewidths of NGC 1333 and B1 gas structures:
  - Star formation feedback correlates with supersonic turbulence at the ~0.01 – 0.5 pc scale
  - B1 filament is a great region to probe turbulence driven star formation theories
<table>
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<tr>
<th>Sampling of Future and Ongoing CLASSy Work</th>
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<tbody>
<tr>
<td><strong>Extend to other CLASSy regions, molecules</strong></td>
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<td>Complete L1451 and Serpens South observations/mapping (Fall), and do same analysis for a complete Perseus picture and Perseus-Serpens comparison</td>
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<td><strong>Complementary approaches to turbulence</strong></td>
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| Explore turbulent energy cascade with statistical analysis of velocity fields:  
  - Two-point correlations statistics (e.g., structure function), PCA |
| **Connection to Magnetic Fields?** |
| Explore effects of magnetic fields on turbulent energy cascade  
  - Observable anisotropies in velocity field scaling laws? |
| **Connection to Dust** |
| Tie gas together with dust to explore virial boundedness of identified gas structures |
| **Morphology and Connection to YSOs** |
| Use dendrogram decomposition for:  
  - Characterizing morphology of dense gas from ~0.01 – 1 pc  
  - Connecting with existing young stellar content |
Results: Cross-Cloud Comparison

Internal gas motions

Barnard 1 vs. NGC 1333

Bulk gas motions