Star Formation Taste Tests

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“Taste Tests”? We frame this project by analogy. How does a great chef, making a complicated dish, know if she has created what she originally intended when she is done cooking? She “tastes.” She informs her cooking with her extensive knowledge of food chemistry (analytic theory), uses all the cooking equipment (simulations) she has in the kitchen to try to make something edible and tasty (starforming, and realistic), and then she uses her senses (observations) to see if what she made tastes as intended. “Tasting” in cooking actually encompasses the joint action of many senses: we propose here a combination of statistical techniques that we call “taste tests.” The tests will allow us to discerningly decide if what we sense (observe) and what we can cook (simulate) might actually be tasty (form stars), and how (analytic theory) that happens.
Getting to “Observational Space”

Includes

- Radiative Transfer
- Projection to 2D sky plane, or “3D” of spectral-line data cubes
- Adding appropriate noise
- Imposing observing characteristics of a telescope

Example:

The Spectral Correlation Function

(Padoan, Goodman & Juvela 2003)
COMPLETE Collaborators, Spring 2007:

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COordinated Molecular Probe Line Extinction Thermal Emission Survey of Star-Forming Regions
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COMPLETE = COordinated Molecular Probe Line Extinction Thermal Emission Survey of Star-Forming Regions

- Is the gas density distribution lognormal or not?
- Meaningful structure in position-position-velocity space
- And scattering! (Cloudshine models)
- Modeling l.o.s. temperature fluctuations
- What stars form from what gas, when?

Meaningful structure in position-position-velocity space
Modeling l.o.s. temperature fluctuations
What stars form from what gas, when?

COordinated Molecular Probe Line Extinction Thermal Emission Survey of Star-Forming Regions
Errors introduced by the assumption of isothermal dust along each line of sight

Variable fraction of emission from transiently heated very small dust grains

Variable dust properties (e.g. emissivity or emissivity spectral index)

Schnee, Bethell & Goodman 2006
Modeling line-of-sight temperature fluctuations

MHD Simulation + Radiative Xfer Code (No NOISE)

\[ A_V \text{ From Emission} \]

![Graphs showing correlation between True \( A_V \) and \( A_V \text{ From Emission} \) for different micron sizes: 60/100 micron and 100/240 micron.]

…and the correlation gets tighter still at longer \( \lambda \)'s

Schnee, Bethell & Goodman 2006
Tasting the Simulations

Modeling line-of-sight temperature fluctuations

Av From Emission

True Av

Av from NIR

Av from NIR

I’ll show you later why that’s “True Av”

Schnee, Bethell & Goodman 2006
Extinction and scattering! (Cloudshine)

L106                      FOSTER & GOODMAN                      Vol. 636
2006

Fig. 1.—L1448 in false color. Component images have been weighted according to their flux in units of MJy sr$^{-1}$. $J$ is blue, $H$ is green, and $K_s$ is red. Outflows from young stars glow red, while a small fan-shaped reflection nebula in the upper right is blue-green. Cloudshine, in contrast, is shown here as a muted glow with green edges. Dark features around extended bright objects (such as the reflection nebula) are the result of self-sky subtraction.

Fig. 2.—L1451 in false color. Again, each component image has been scaled to the same flux scale in units of MJy sr$^{-1}$, and $J$ is blue, $H$ is green, and $K_s$ is red. A smaller map of 2.2 mm dust emission contours from COMPLETE (M. Tafalla 2006, in preparation) has been overlaid, showing that the color of cloudshine is a tracer of density. Redder regions have high dust continuum flux, and the edges of cloudshine match the edges of the dust emission. Dark edges around bright features (particularly noticeable along the northern edges) are the result of self-sky subtraction.
Fig. 3.—Model of cloudshine in one core as reflected interstellar radiation. The lower left panel shows the roughly circular feature we chose to model as a sphere. Due to the surrounding structure, only the left half of the circle was used to derive an angle-averaged radial profile. The comparison between this radial profile and our best-fit model (an $r^{-2}$ density profile and a total optical depth of 120 mag of visual extinction) is shown in two ways: above as radial flux profiles in individual bands and in the lower right as a synthetic color-composite image that allows for an overall comparison. Although the fit is good, the central region of the core is darker than predicted by the model. Some of this may be due to self-sky subtraction in the image (which causes dark edges around bright features) and a nonspherical, nonisotropically illuminated core, and some may be due to a failure to adequately model the density structure at the center of the core.
Extinction and scattering! (Cloudshine)

Tastes “right”, with 20% scatter, at 1<A_v<10, for NIR.

Padoan et al. 2006
Where am I?

Meaningful structure in position-position-velocity space (3D)

Modeling l.o.s. temperature fluctuations

And scattering! (Cloudshine models)

Spectral-Line Data:
The 2D (bland) & the “3D” (Spicy) Views

Is the gas density distribution lognormal or not? (2D)

Meaningful structure in position-position-velocity space (3D)

What stars form from what gas, when?
position-postion-velocity is **NOT the same as**
position-position-position-velocity-velocity-velocity

**cf. Ostriker, Stone & Gammie 2001**

mm peak (Enoch et al. 2006)
sub-mm peak (Hatchell et al. 2005, Kirk et al. 2006)
$^{13}$CO (Ridge et al. 2006)
mid-IR IRAC composite from c2d data (Foster, Laakso, Ridge, et al. in prep.)
Optical image (Barnard 1927)

3D rendering courtesy AstroMed team at IIC (Borkin, Halle, Kauffmann, Alán, Goodman)
Is the gas density distribution lognormal or not? (2D)

The (secret) uncertainties inherent in column density mapping.

Goodman et al. 2007
★Extinction & thermal emission are log-normal-ish & more so when non-$^{13}$CO detected points are included.

★$^{13}$CO is not a very faithful tracer of column density.
Meaningful structure in position-position-velocity space (3D)

Dendrogram
(Rosolowsky et al. 2007; cf. Houlanhan & Scalo 1992)

CLUMP FIND
(Williams et al. 1994)
Meaningful structure in position-position-velocity space (3D)

(Dendro)Surfaces

“CLUMPFIND”

Observed Reality

“Observed” Simulations

work of Rosolowsky, Pineda, Kauffmann, Borkin, Padoan, Halle & Goodman;
figure from Goodman & Rosolowsky NSF “Star Formation Taste Tests” Proposal, Fall 2006
Is CLUMPFIND OK as a Statistic? (Like Cayenne Pepper?)

CLUMPFIND output for L1448 with 1.2K step & threshold!
(Lower values give too many clumps to show!!)

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<th>Threshold</th>
<th>Step size</th>
<th>total number of Clump</th>
<th>% above sensitivity limit Mass v/s Radius</th>
<th>% above sensitivity limit FWHM v/s Radius</th>
<th>% above both curves</th>
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Dendrograms: A Physical Hierarchy?

The “self-gravitating” parts of L1448:

And, coming soon, to a cookbook (Journal) near you...
(3D PDF)
Which “stars” “form” from what gas, when?

"'Cause if my eyes don't deceive me,
There's something going wrong around here"

--Joe Jackson
What stars form from what gas, when?

Theorists using Observers Ingredients

e.g. Schmeja & Klessen 2006
Are you hungry yet?
Who can make this?