Taurus: Then and Now

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Dense Cores in Dark Clouds LXV
for Phil Myers
21 October 2009
Taurus - poster child for star formation

- Interplay of observations and theory in Taurus greatly advanced star formation theory

- Understanding the structure of Taurus was key. Phil led the way by relating optical obscuration in filaments to dense cores, and relating dense cores to star formation
Early steps in opaque filaments & cores

Survey a dozen `opaque' points along the B18 filament for dense gas tracers NH3 and HC5N. Below is map of ‘fragment’ TMC-2 L~0.1pc, N~4x10^4 cm^{-3}, M~1Mo, dv=0.2 km/s

Cylinder model of B18 filament

2 cylinders, Less dense outer cyl (2x5pc, n<700/cm³) and denser inner cyl (3000/cm³) with 9 T Tauri stars. Myers 1982, ApJ, 257, 620
Other SF news in late 70’s
L1551 bipolar outflow in Taurus

Collapse models/ initial conditions

• Before Phil,
  – typical theory starting state
    n = constant, unstable cloud,
    1Mo cloud forms 1Mo star

• Phil’s work greatly influenced our theory (Frank Shu, me) in setting better initial conditions
  – Thermal (T~10K) 0.2 km/s,
  – in near equilibrium with gravity n~1/r^2.
  – Mcloud > Mstar
THE COLLAPSE OF THE CORES OF SLOWLY ROTATING ISOThERMAL CLOUDS

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ABSTRACT

Rotation plays an important role in the formation of stars and planetary systems, but detailed calculations of its effects have been limited by the difficulty of following the collapse from interstellar dimensions to those characteristic of the solar system or binary stars. We present here a semianalytic perturbational solution for

\[ \rho(r) = \frac{a^2}{2\pi Gr^2}, \]  

(1)

\[ \bar{\rho}(R) = \frac{3}{4\pi R^3} \int_0^R \rho(r)4\pi r^2 dr = \frac{3a^2}{2\pi GR^2}. \]  

(2)

Myers and Benson (1983) quote mean values of temperature \( T = 10.5 \) K and ammonia linewidth (FWHM) = 0.32 km s\(^{-1}\), which correspond to an equivalent sound speed (in a cosmic molecular gas including turbulence) \( a = 0.22 \) km s\(^{-1}\). On the other hand, if we
Snapshot of collapse (~0.1pc) looks radial on outside. L (ang. mom.) conserved leads to disk on AU scales.
Are they Protostars? adventures with Phil


- Snapshot survey of 25 IRAS-Dense cores in CO for circumstellar emission with Owens Valley interferometer. 64% show CO outflow structure on small (~1000 AU) scales. H2O masers seen on 100AU scales.

<table>
<thead>
<tr>
<th>No.</th>
<th>IRAS</th>
<th>Core</th>
<th>R.A.(1950)</th>
<th>Decl.(1950)</th>
<th>$V_{lsr}$ km s$^{-1}$</th>
<th>$D$ (pc)</th>
<th>$L_{IR}$ ($L_\odot$)</th>
<th>OVRO Snapshot</th>
<th>FCRAO</th>
<th>Ref. FCRAO</th>
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</table>
Global view: IRAS sources in Taurus

More phil-aments in Taurus


Interpret filaments using IRAS 60um/100um at 5’ resolution
Taurus

IRAS 100um
HIRES 2’ resolution
(see my poster)

100um point sources (youngest) are embedded in the filaments

Looking forward: want a complete survey of dense gas
Taurus: Now
….with Spitzer

- Taurus Legacy Survey
  - 44 sq deg
  - Padgett et al 2009
    - overview
  - Rebull et al 2009
    - census of old & new YSOs
    - analysis of 160um emission
    - (see my poster)
Synergies of Multiple Surveys

- **Spitzer Space Telescope**: MIR/FIR survey determines the state of circumstellar material for all stellar and substellar members including edge-on disks too faint for IRAS.

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<th>IRAC</th>
<th>MIPS</th>
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<td>70</td>
</tr>
<tr>
<td>θ</td>
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<tr>
<td>1.7”</td>
<td>6”</td>
<td>18”</td>
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</table>

- **CFHT and SDSS**: Optical surveys identify very low mass stellar members and brown dwarfs and provide accurate griz & I, z band photometry with better than 1“ resolution; SDSS spectral scans as well

- **XMM-Newton**: X-ray survey penetrates tens of magnitudes of visual extinction, identifies potential WTTS, measures effect of stellar activity on circumstellar environment

- **FCRAO**: Millimeter survey of $^{12}\text{CO}$ and $^{13}\text{CO}$ at resolution of 45” and unsurpassed sensitivity provides molecular cloud context for point sources
Taurus by name

From FCRAO 12CO/13CO survey
Taurus Spitzer Legacy

24 μm 6"
160 μm 57"
13CO 47"

Padget et al 2009 (Spitzer)
Goldsmith et al 2008, Naranyan et al 2008 (FCRAO)

7 deg 17 pc
Compare cloud pixel by pixel to get $T_{\text{dust}}$ in $1^\circ \times 2^\circ$ field centered on L1521F.
Dust temperature

Td = 14.2 K from linear fit

1.1' matched spatial resolution
Given $T_{\text{dust}}$ now get optical depth at $160 \, \mu m$

$I_\nu = \tau_\nu B_\nu(T)$

Use image data $I_{160}$
Use $T$ from slope $I_{160}/I_{100}$

$\Rightarrow \tau_{160}$

$\delta A_V = 1, 2, 4$
160 $\mu$m opacity

\[ \tau_\nu = \kappa_\nu \rho L \]

Use ratio at 2 wavelengths $A_\nu/A_{160}$ to get $\kappa_{160}$

\[ \kappa_{160} = 0.23 \text{ } cm^2 \text{ } g^{-1} \]

Consistent with commonly assumed values for submm opacity in dense cores for $\beta = 2.$

& 2.6 times higher than diffuse ISM opacity
Similar to dense core opacity adopted by other groups

- OH5 Ossenkopf & Henning 1994, Evans et al. 2001
- Diffuse ISM Weingartner & Draine 2001
- Taurus @160μm
- Mg/Md=124
- Kirk, Ward-Thompson, & Andre 2005
Decompose into cold cloud & cold core
Cold cores

Cold cloud

$\tau_{160}$
Processed 160µm data reveals
Cold dense cores (10K-ish)
Cold cloud (14.2K)

Terebey et al 2009
Youngest YSOs are coincident with cold cores that are found in filaments (1’ resolution)
Closing remarks

Taurus continues to shed light on star formation

and...Thank you Phil

For being a great scientist
And a genuinely nice guy

There couldn't be a better combination
160μm cold cores have counterparts

<table>
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<th>Dec.</th>
<th>l</th>
<th>b</th>
<th>A_V</th>
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<th>C&lt;sup&gt;18&lt;/sup&gt;O Core&lt;sup&gt;2&lt;/sup&gt;</th>
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Av clumps - Dobashi et al. 2005
C<sup>18</sup>O cores - Onishi et al. 1998