Centimeter Wave Star Formation Studies in the Galaxy from Radio Sky Surveys

W. J. Welch
Radio Astronomy Laboratory, Depts of EECS and Astronomy
University of California
Berkeley, CA 94720
Tel: (510) 643-6543
Fax: (510) 642-3411
wwelch@astro.berkeley.edu

Co-authors:
Richard Crutcher, University of Illinois
Edward Churchwell, University of Wisconsin
Melissa Enoch, University of California, Berkeley
Paul Goldsmith, JPL

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I. Introduction

Stars are the major building blocks of the Galaxy and the Universe. There has been a major effort to understand star formation since the discovery of heavy molecules in the Interstellar Medium demonstrated both the existence of molecular hydrogen clouds and that these clouds were the locations of star formation. Much is now known about the circumstances of star formation, but the actual process of the stellar birth is not understood. For example, Lada et al, 2008, as well as others, have found that the small core mass spectrum in molecular clouds resembles the Initial Mass Function for stars and may directly give rise to the stellar IMF. However, little is known about how the cores actually evolve into single stars or groups. There are presently a number of surveys aimed at understanding the process. Current examples are the legacy surveys on the James Clerk Maxwell Telescope (e.g. Plume et al, 2007) at millimeter and sub-millimeter wavelengths and the Spitzer Spacecraft Infrared Surveys (e.g. Evans et al, 2003). These studies provide good coverage of many important molecular tracers. Very high angular resolution observations can be obtained with the millimeter interferometers, e.g. CARMA, PdB and SMA , but generally it is difficult for the short wavelength telescopes to cover significant large fields of view. Many of the surveys are focused on regions where formation of many stars is already underway, and it is difficult to disentangle the various stages.

II. Prestellar Cores

Probably the most important stage to study is the earliest stage, the prestellar core stage, to understand what initiates the formation of stars. One needs to study a number of cores at various stages from no collapse to full scale collapse. Spectral line maps reveal line-of-sight collapse motions. Relative molecular line strengths provide the kinetic temperature and density distributions of the molecular hydrogen. Nearby core sizes are a few minutes of arc requiring observations with angular resolutions as good as 20” - 30”.

A few cases have received detailed investigation.TMC-1C in Taurus (Schnee et al. 2007) is a starless core which shows a rich molecular chemistry around one or two dense dust cores with evidence of both infall and rotation. It has begun to form one or a few stars. Another recent extensively studied example is the core in the dark cloud in L1551 (Swift and Welch, 2008). This core is well enough separated from the other parts of its cloud that its current state and the influence of its surroundings can be readily understood. Its gravitational potential exceeds its kinetic energy so that it should be in the state of collapse. Yet it does not show all the expected signs of collapse. There is a weak infall signature in the CS(2-1) line which is only in the outer part of the core. Yet the N_2H+ in the interior core shows no sign of collapse. Thus the anticipated inside-out collapse is not yet evident. The central temperature is quite low, about 9K, so there is little excess pressure. There is little evidence of turbulence in its surroundings, and there is no sign of turbulent flow driving the star formation. These are two examples of cores at different stages, and it will require the study of many more at different stages to elucidate the process. More such cores need to be found. One or more surveys of semi-quiescent regions like the Taurus Molecular Clouds is required.

III. Importance of CM Wave Interferometry.

There are particular reasons why large scale star formation surveys of molecular clouds at centimeter wavelengths are important and complementary to the mm/submm observations. The young molecular clouds where low mass stars form have a rich carbon chemistry and can be studied in the emissions of long chain molecules, such as the cyanopolyynes, $HC_{2n+1}N$. These heavy molecules have spectral lines at centimeter wavelengths which are readily observable. Other useful molecules, such H_2CO and OH, are also observable at centimeter wavelengths. An interferometer array of antennas will have a wider field of view at centimeter wavelengths because the primary antenna beams are typically much broader than those of the typical millimeter wave antennas. For example, the ALMA 12m dishes have a beam of one arc minute at 100 GHz. That same 12m dish at 10 GHz has a beam solid angle that is 100 times larger. Surveys of tens of square degrees by multiple pointing of the interferometer antennas will be practical with cm arrays and virtually impossible with ALMA.

There are good prospects for detecting prestellar cores in maps of the long chain molecules. The molecule HC_3N has its lowest rotational transition at 9.1 GHz. This transition has three hyperfine components spread over just three MHz. Measuring the relative strengths of the three lines can give the optical depth and the excitation temperature, in this one transition. An estimate of the line strength based on observations of part of the TMC1 cloud in Taurus in a higher rotational transition by Pratap et al(1997) predicts a high signal/noise for a cm wave array of reasonable size in the 9.1 GHz line. Figure 1 shows a part of the Taurus cloud region that contains both TMC-1 and Ll551. A survey of many tens of degrees would be valuable here, and it could be done with a cm wave array, such as the Alan Telescope Array, in a reasonable amount of time.

A second example is the observation of the HC_5N molecule in its lowest four rotational transitions at 2661 MHz, 5324 MHz, 7888 MHz, and 10,650 MHz. Having these four transitions mapped at one time permits modeling the molecular hydrogen density and excitation distributions as well as the abundance of the HC_5N. For example, as shown in Figure 2, a study of the ratio of the strengths of the lowest and highest frequency transitions would provide a very accurate measure of the density of the medium, nearly independent of the gas temperature. Combining observations in the other two transitions can then provide good measures of the kinetic temperature of the gas. At these low frequencies the molecular A values are substantially lower than is typical for the millimeter wave transitions. There is significant excitation of these lines at molecular hydrogen densities as low as 100 cm^{-3} as well as at higher densities.

IV. Magnetic Field Measurements

A further important low frequency mapping program is the observation of the molecular Zeeman splitting to study the cloud magnetic fields. Magnetic fields are known to be ubiquitous and may or may not have a profound effect on the star formation process. Whether the fields are strong enough to play a role requires a program of surveys in these molecular clouds. The low frequencies are a good choice for these studies because the thermal line broadening is smaller than it would be at mm wavelengths. For the dense cores, the C_2S transition at 22.4 GHz is a good choice. This is a transition with high critical density, $\sim10^5$ H_2

mols/cc, which corresponds to the densities of regions in which star formation is currently underway.

The bulk of the matter in molecular clouds is at low densities, 100 H_2 mols/cc or less, and Zeeman splitting observations of HI and OH would sample the magnetic fields in these regions very well. The overall program would allow the measurement of mass to magnetic flux ratio over entire clouds and the spatial variation with density could be studied, going beyond the usual studies of just the cores. The field strengths by themselves can yield the ratio of random to uniform magnetic field strengths, which addresses whether magnetic or turbulent pressure dominates. The ambipolar diffusion model of core formation requires that the mass to magnetic flux ratio increase from envelope to core, and the data could test this model. Very Large scale mapping is required to cover the extended lower density clouds.

V. Required Instrumentation

A CM Wave Interferometer is required to provide the 20" – 30" angular resolution discussed above. Frequency agility, the ability to operate at all frequencies in the range of the instrument, is essential to be able to observe any of the 100's of useful spectral lines. The EVLA will have the agility when it is complete. The ATA has the frequency agility and the resolution for the star formation studies. When it is built out, it will have collecting area comparable to the EVLA. It will not have the VLA resolution, but it will be a superior survey instrument, covering a much greater field of view in each pointing. It can also observe in all of its four bands at once.

References: R. Plume et al, 2007,PASP, 119, 102P.
N. Evans et al, 2003, PASP, 115, 965-980.
S. Schnee et al, 2007 ApJ, 671, 1839-1857.
C. Lada et al, 2008, ApJ, 672, 401L.
P. Pratap,et al, 1997, ApJ, 486, 862P.
J. Swift and W. Welch, 2008, ApJS, 174, 202S.
Welch et al, 2009, IEEE, special issue, in press
R. Crutcher and T. Troland, 2007, IAUS, 237, 141C.

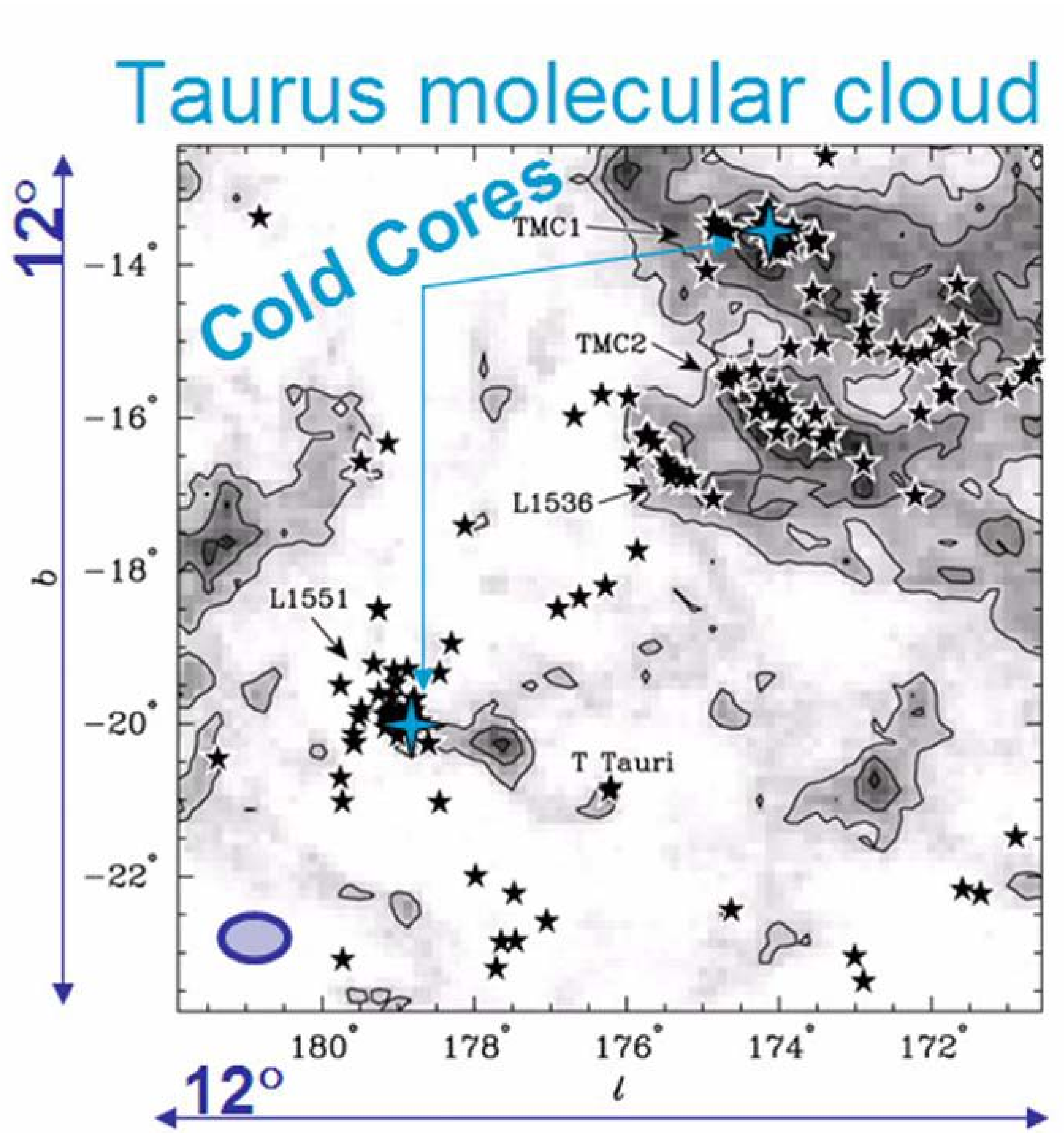

Figure 1. This is a low resolution CO(1-0) map of a part of the Taurus molecular clouds. Young TTauri stars are shown as the star symbols. The ellipse in the lower left corner is the ATA FOV at 9 GHz, slightly larger than the entire L1551 dark cloud.

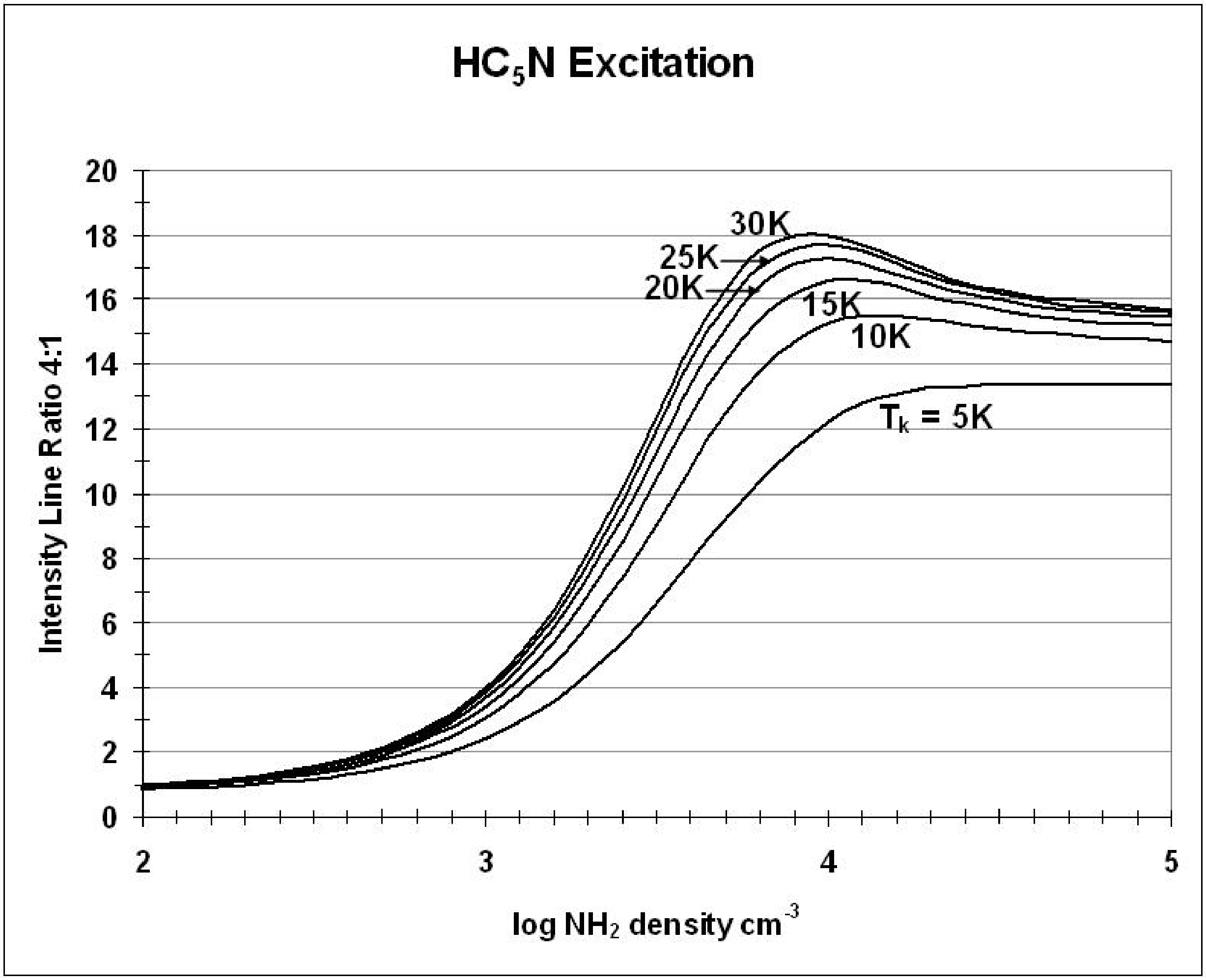

Figure 2. The 4:1 line ratio of the HC_5N molecule. The abscissa is the molecular hydrogen density. The line ratio gives the H_2 density with very little dependence on the kinetic temperature up to about 10^4.