The California Molecular Cloud: A Giant Sleeps

Student
Advisor: Advisor
Proposed Comittee: Recommendation 1, Recommendation 2, Recommendation 3

ABSTRACT

I propose to use infrared and radio data to provide a detailed characterization of the structure of and star formation in the California Molecular Cloud. There is a great deal of interest in understanding star formation as it is still an unsolved problem and is fundamental to most, if not all, of astronomy. Observations of the California Molecular Cloud allow us to study a neglected star formation environment: high mass giant molecular clouds with low star formation rates. Using extinction maps and surveys of the cloud in the millimeter with CO, the far infrared with *Planck* and *Herschel* PACS/SPIRE, the mid infrared with *WISE*, and the near-infrared, we will study the physical and kinematic structure of the California Molecular Cloud in unprecedented detail. Due to its high quality and coverage, with infrared data we will create the most complete census of protostars in California to date. We will also use the aforementioned data to determine relationships between the distribution of star formation activity and the physical properties of the California Molecular Cloud.

1. Introduction

The process of star formation in interstellar gas is of fundamental importance in astrophysics. We still do not have a predictive theory of star formation that works on either local or extragalactic scales. Constraining our understanding of star formation is necessary as it provides part of the foundation for understanding astrophysical processes as varied as planet formation, the evolution of galaxies over cosmic time, and even the epoch of reionization. Stars are observed to form in giant molecular clouds (GMCs) which form from the diffuse interstellar gas. A necessary ingredient for constraining a theory of star formation is understanding the relationship between properties of the interstellar gas in the GMC and the rate at which the gas is turned into stars, the star formation rate (SFR). Fifty years ago, Schmidt (1959) proposed that the SFR surface density scales as a power-law of the surface density of gas — $\Sigma_{SFR} \approx \kappa\Sigma_{gas}^{\beta}$ (power-law index β, normalization κ). The Schmidt law can be considered in two regimes: as a *local* Schmidt law relating Σ_{SFR} and Σ_{gas} within an individual cloud, and as a global Schmidt law relating the Σ_{SFR} and Σ_{gas} on spatial scales of entire galaxies. The surface density of gas is commonly measured with extinction (the reddening/dimming of background stars), dust continuum emission in the far-infrared (FIR), and radio/submillimeter spectral line tracers such as CO (Goodman et al. 2009). Locally, SFRs can be determined by counting young stellar objects (YSOs) in GMCs since we can determine their ages quite well by comparing them with pre-main sequence stellar (PMS) models. To understand star formation, it is clear that we need to study the environments in which stars form: giant molecular clouds.

Studies of GMCs will provide insight into the physical relationships between the physical properties of the cloud and its SFR. Systematic studies of local GMCs have found that the ratio of the SFR within a GMC and the GMC mass can vary by an order of magnitude (Lada et al. 2010). The correlation is better when we just consider the dense gas ($n_{H2} \gtrsim 10^4 \mathrm{cm}^{-3}$). Lada et al. (2010) found that there exists a relatively tight linear correlation in SFR vs dense gas mass. This result suggests that the structure of GMCs may play an important role in determining the SFR. Lada et al. (2013) confirmed this by showing that for individual clouds that could be fit by the same local Schmidt law (same β and κ), the differences in the SFRs are primarily due to differences in the cloud structure. They also showed that a global Schmidt law between clouds does not exist, both observationally and as a consequence of Larson's 3rd Law (Larson 1981; Lombardi et al. 2010), which is an empirical relationship between gas density and cloud size, $n \sim L^{-1.1}$.

One limitation in these studies is the resolution of the extinction maps. The extinction maps were created with the NICEST method (described in Lombardi (2009)) which measures extinction by determining the change in the near-infrared (NIR) color of extincted background stars relative to a nearby sample of unextincted background stars and uses statistical methods to recover some of the small scale structure. This is still limited, however, by the density of background stars, which decreases at high A_K and small angular scales. Current extinction studies, which have been the best way to measure gas column densities (Goodman et al. 2009), are currently limited to a $K-$band extinction (A_K) of ∼2–3 magnitudes at just over arcminute resolutions. Because the densest gas is often confined to small clumps, low resolution studies will not always resolve it, which can limit our understanding of how star formation is distributed in a GMCs. An alternative to extinction is dust emission, which is also a good tracer of gas (Goodman et al. 2009). *Herschel* allows us to probe smaller angular scales and deeper using dust emission, down to $A_K \sim 30$ at .5 arcminute resolution (Lombardi et al. 2014). Using *Herschel* , Lombardi et al. (2014) found that the derived Schmidt law index, β can be influenced by the resolution of gas surface density map, indicating that achieving high resolution is important for understanding how the star formation is distributed in the cloud.

While systematic studies of regions with appreciable star formation have been done for a long time, massive low SFR clouds have been neglected. Massive low SFR clouds provide important laboratories for studying star formation and the origin of the dense gas in GMCs (Forbrich et al. 2009; Lada et al. 2012). Two clouds that exemplify this class are the Pipe Nebula (Forbrich et al. 2009) and the California Molecular Cloud (Lada et al. 2010). These clouds have SFRs much lower than clouds of similar mass and distance. In the high SFR regime of GMCs, Orion is likely the most well studied GMC. California is quite similar to Orion in terms of mass and distance, which makes it an excellent object for comparison. A comparison of these two clouds would provide insight into how the properties of GMCs affect their star formation activity. A first step in ultimate pursuit of this goal is to better characterize the California Molecular Cloud (Lada et al. 2009) which is the most massive giant molecular cloud within ~ 0.5 kpc.

2. California Molecular Cloud

Lada et al. (2009) were the first to recognize the California Molecular Cloud (CMC) as a GMC separate from the Perseus and Taurus clouds. It was first revealed by the relatively large and uniform surface density of foreground contaminant stars. Additional confirmation came from CO data showing it was a coherent velocity structure and possessed a larger radial velocity than the clouds it was previously associated with. Despite its proximity, it went unnoticed for so long because it has a particularly low SFR and had not been the target of intense study.

2.1. Major Studies of the CMC

Lada et al. (2009) were the first to do a study of the basic physical properties; determining its distance, size, mass, structure, and star formation rate. It was determined to be as distant and as massive as Orion A (which has one of the highest SFRs). Structure and mass were measured using extinction maps created with the NICEST method of Lombardi (2009). The level of star formation was estimated using 25 IRAS point sources in California that were identified as YSOs. They determined that the star formation activity was very modest and was localized to the thin spine of dense gas in the cloud. Using CO data from Dame et al. (2001), they showed remarkable agreement in structure between the integrated CO and extinction maps as well as a modest velocity gradient in the cloud. Lada et al. (2010) updated their accounting of the star formation with x-ray, optical, and infrared identified YSOs near the emission line star LkHα 101 (Wolk et al. 2010), increasing the number of YSOs to 279, and calculated the SFR using a median age of ∼2 million years. The SFR is small compared to other GMCs of similar size. The primary limitations of these studies were spatial resolution and an incomplete accounting of the star formation due to the low sensitivity of IRAS maps and spotty coverage of YSO surveys in California.

Later studies (Harvey et al. 2013; Broekhoven-Fiene et al. 2014) attempted to do significantly better, particularly in terms of their accounting of the star formation. Harvey et al. (2013) used new 18.5 deg^2 *Herschel* maps of the cloud to get a higher resolution and more sensitive view of the star formation and dense gas structure. The resolution of the *Herschel* maps spans from a few to a few tens of arcseconds depending on which band is used. This allowed Harvey et al. (2013) to identify 60 point sources in the cloud, 49 of which matched point sources identified with *Spitzer* as YSO by Broekhoven-Fiene et al. (2014), which Harvey et al. (2013) had access to before publication. All of the Harvey et al. (2013) YSOs are located in regions of relatively high density. The *Herschel* maps also allowed for a study of the structure at a high dynamic range, extending the density distribution out to $A_K \sim 4$. However, when determining the relationship between YSO surface density (Σ_{YSO}, which is directly related to Σ_{SFR}) and gas surface density, they smoothed their extinction and YSO maps down to 0.2° to get better statistics with their sparsely populated YSO map (only 60 sources). At the same time, smoothing limited them to $A_K < 1$; and they were unable to take advantage of the full dynamic range of the *Herschel* data.

Broekhoven-Fiene et al. (2014) studied star formation in the cloud using the IRAC and MIPS cameras on *Spitzer* to study most of the cloud at resolutions even higher than *Herschel*. IRAC covered 2.5 deg^2 and MIPS covered 10.47 deg^2 and they identified 166 YSOs. The Spitzer coverage was incomplete, covering only a fraction the cloud area.

3. Proposed Study

Our knowledge about the CMC has increased since its identification by Lada et al. (2009). There is still, however, a continuing need for a better characterization of California's surface gas density and star formation activity. There have also been no high resolution kinematic studies that encompass the majority of the cloud. This proposal aims to remedy this situation. The primary focus is to measure the physical and kinematic structure with greater detail than previous studies and to get as complete and clean a census of the star formation within the California molecular cloud as possible.

Like Harvey et al. (2013) we will leverage the large coverage and depth of the *Herschel* maps to complete an improved study of the structure in the cloud using the methodology of Lombardi et al. (2014). This will be a significant improvement over the analysis of Harvey et al. (2013) since the method of Lombardi et al. (2014) does not require smoothing the data to 0.2° for any part of the analysis, which will allow us to take advantage of the full dynamic range in the *Herschel* maps. Following the methodology of Lombardi et al. (2014), the relative flux maps from *Herschel* will be calibrated against *Planck* absolute fluxes, convolved to a common resolution (the 36"of SPIRE 500μm) and converted to maps of extinction, A_K, by performing a SED fit pixel by pixel, with a simple modified blackbody, $\tau_\nu B_\nu(T)$, where τ_ν is a power-law in frequency. The *Herschel* optical depths are converted to A_K using a calibration derived from 2MASS extinction data.

As an upgrade in resolution and depth to the 2MASS extinction maps, we will also use a new NEWFIRM JHK_S survey of 11 deg^2 (Figure 1, red) of California to create new maps using the NICEST method. NEWFIRM is a NIR wide-field imager mounted (when the data was taken) on NOAO's 4m telescope on Kitt Peak. on The survey is designed to reach a depth of 20 mag in K_S, 5 mags deeper than 2MASS (Skrutskie et al. 2006), which increases the density of visible extincted background stars. The resulting higher resolution will allow us to look at the structure, distribution, and properties of protostars in much greater detail. NEWFIRM's depth and resolution will allow us to see a higher density of background stars which enables us to reach angular scales of $30-40$" on the extinction map. The resolution of the NEWFIRM extinction maps, being superior to the 2MASS extinction maps, will also allow for a more direct comparison with the *Herschel* maps (36" resolution) and will mitigate some of the effects of low resolution on the observed cloud structure.

Herschel will also be able to help with studying the star formation activity in California. Taking advantage of the high dynamic range of *Herschel*, we can identify dense cores in California as high density peaks in the cloud. Once the cores are extracted (possibly via a spatial filtering method, see Alves et al. (2007) for an example) and masses measured, we will determine the core mass function, which is thought to be related to the initial mass function (Alves et al. 2007). To obtain the full spatial coverage at shorter infrared wavelengths that *Spitzer* did not obtain, we will combine *Herschel* and *WISE* data. This data, with the *Spitzer* data too, will be used to locate protostars and determine their SEDs to ensure that we are getting as complete a census of the star formation as possible.

Because our *Herschel* extinction map is calibrated using a reliable tracer of column density (extinction), the probability distribution function (PDF) of gas column densities derived from our data will be a more accurate representation of the cloud structure than previous studies (Lada et al. 2009, 2013; Harvey et al. 2013). When combined with the distribution of protostars, we will be able to measure the shape of the relationship between Σ_{YSO} and Σ_{gas} and determine the Schmidt law in California at a higher angular resolution than previous studies.

We also have Arizona Radio Observatory Submillimeter Telescope on-the-fly mapping observations of the CO (2-1) transition of approximately 6 deg^2 (Figure 1, blue) of California in the star forming regions, which I will reduce and analyze. The data itself is split into three regions, following a filamentary structure, which systematically varies from low to high SFR, that connects to the large star forming region around LkHα 101.

These regions have each have different SFRs and it will be interesting to see how the velocity structure in the various tracers differs in these three regions. Our observations specifically cover ^{12}CO, ^{13}CO, and C^{18}O J(2-1) lines so that we can understand the kinematics and structure at different levels of density. ^{12}CO is very optically thick and only probes the low density gas, but the other two isotopologues are much rarer and thus probe higher densities (Goodman et al. 2009). With three isotopologues and three regions, we are in an excellent place to study how each CO isotopologue relates to the gas and dust properties and how that varies across the cloud (Pineda et al. 2008; Ripple et al. 2013). CO is such a commonly used line in astrophysics, used to study everything from protoplanetary disks to entire galaxies, that understanding it as a tracer of molecular gas, dust, and star formation is important. The rarer isotopologues will enable us to probe the kinematics of the high density structure in the cloud, in particular the dense cores (Alves et al. (2007)) and protostars. In general, we hope to use the CO data to understand the kinematics of the gas; observing (in/out)flows, large scale gradients, and turbulence, in addition to the kinematics of cores (Lada et al. 2008).

In summary, studies of the California Molecular Cloud have shown that the cloud has a low dense gas fraction and a low star formation rate. We aim to do a complete, cohesive study of the California Molecular Cloud covering its structure, dust and gas properties, distribution of protostars, and velocity structure. This study will allow detailed comparisons with Orion and other molecular clouds leading to a better understanding of how the properties of GMCs and their gas affect star formation.

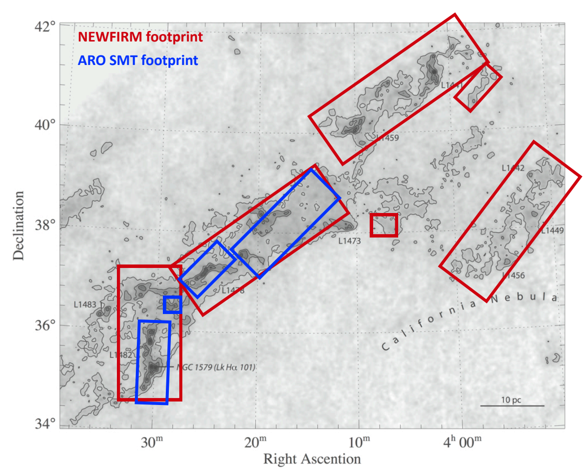

Fig. 1.— The California Molecular Cloud in extinction with observation footprints.

REFERENCES

Alves, J., Lombardi, M., & Lada, C. J. 2007, A&A, 462, L17

Broekhoven-Fiene, H., Matthews, B. C., Harvey, P. M., et al. 2014, ApJ, 786, 37

Dame, T. M., Hartmann, D., & Thaddeus, P. 2001, ApJ, 547, 792

Forbrich, J., Lada, C. J., Muench, A. A., Alves, J., & Lombardi, M. 2009, ApJ, 704, 292

Goodman, A. A., Pineda, J. E., & Schnee, S. L. 2009, ApJ, 692, 91

Harvey, P. M., Fallscheer, C., Ginsburg, A., et al. 2013, ApJ, 764, 133

Lada, C. J., Muench, A. A., Rathborne, J., Alves, J. F., & Lombardi, M. 2008, ApJ, 672, 410

Lada, C. J., Lombardi, M., & Alves, J. F. 2009, ApJ, 703, 52

Lada, C. J., Lombardi, M., & Alves, J. F. 2010, ApJ, 724, 687

Lada, C. J., Forbrich, J., Lombardi, M., & Alves, J. F. 2012, ApJ, 745, 190

Lada, C. J., Lombardi, M., Roman-Zuniga, C., Forbrich, J., & Alves, J. F. 2013, ApJ, 778, 133

Larson, R. B. 1981, MNRAS, 194, 809

Lombardi, M. 2009, A&A, 493, 735

Lombardi, M., Alves, J., & Lada, C. J. 2010, A&A, 519, L7

Lombardi, M., Bouy, H., Alves, J., & Lada, C. J. 2014, arXiv:1404.0032

Pineda, J. E., Caselli, P., & Goodman, A. A. 2008, ApJ, 679, 481

Ripple, F., Heyer, M. H., Gutermuth, R., Snell, R. L., & Brunt, C. M. 2013, MNRAS, 431, 1296

Schmidt, M. 1959, ApJ, 129, 243

Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163

Wolk, S. J., Winston, E., Bourke, T. L., et al. 2010, ApJ, 715, 671

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