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The structure of molecular clouds

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Abstract. The formation of stars is inextricably linked to the properties of their parental clouds. It is still not entirely understood what causes different modes of star formation (clustered or isolated) in giant molecular clouds. For example, are the turbulent properties the determinant factor or are feedback mechanisms decisive? Here we will give a brief overview of possible observational techniques (molecular line observations, dust continuum emission, scattered infrared light, extinction mapping techniques) to study the structure and properties of giant molecular clouds and will briefly discuss their advantages and disadvantages. We will then concentrate on our recent efforts to determine the first ever all-sky extinction maps based on near infrared excess of star light. First results of our investigation of the structure of all giant molecular clouds in the solar neighborhood show that there are significant differences in the column density distribution between clouds in the low A_V regime at a spatial scale of 0.1 pc. At higher extinction values, dominated by material most likely involved in ongoing star formation, the column density distributions are very similar. We also find that star formation has a typical threshold of 4-8 mag of optical extinction and that the overall star formation efficiency of giant molecular clouds is in the order of a few tenths to a few percent.

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1. Introduction

Understanding the formation of stars is one of the main challenges in astrophysics. The vast majority of current day star formation happens within giant molecular clouds (GMCs), where stars form either as massive dense clusters, loosely bound stellar groups or individual isolated stars. Investigating the structure of GMCs will help us to get an insight into causes for the occurrences of these different star formation modes, as well as other important properties such as the initial mass function, the star formation efficiency and the binary fraction.

The mass of GMCs is mainly contained in molecular Hydrogen and Helium atoms. About one percent is made up of dust, typically silicates and/or graphites. Furthermore, a variety of other molecules and their isotopes have been detected. Amongst them are e.g. CO, NH_3, CN, H_2O, with CO being the most abundant. The total masses of GMCs vary from about 10^3 to 10^6 solar masses, similar to their sizes which range from a few up to 100 pc. Typical temperatures in the clouds range from 10 K to 30 K.

It has been realised that large scale random bulk motions of material – turbulence – dominate over thermal motions within the clouds. Hence, the structure of GMCs seems to be determined by gravity and turbulent motions. Only on the small scales of protostellar cores does thermal motion dominate. Turbulence decays on very short timescales. Hence, its energy has to be constantly replenished. The sources for this energy are still under debate. Best candidates are supernovae explosions, radiation of massive stars, outflows from young stellar objects, as well as gravitational and magneto-rotational instabilities. In the overall picture, certainly all of them play their role, depending on the environment and the size scale we are interested in.

Following Kolmogorov (1941), turbulent energy in the clouds cascades down from large scale flows to smaller scales. It is statistically self-similar at all scales. This energy transfer within the cloud material leads to a fragmentation process into clumps and cores. Such a process seems to set the initial mass function of the stars, allready early on in the formation process. Evidence of this has been found by e.g. Alves et al. (2007). Their investigation of cores in the Pipe nebula shows that the core mass function can be scaled by a factor of three to obtain the initial mass function.

A more global approach than to look at the core mass function is to determine the distribution of material in the entire cloud, which can be described by the structure function of the material. Analytical (e.g. Kolmogorov 1941) and numerical simulations of turbulence (e.g. She & Leveque 1994; Boldyrev 2002) provide us with models for the structure functions of clouds with different turbulent properties. These can then be used to determine which turbulent model can best explain observational data of real molecular clouds. This has recently been done by e.g. Lombardi et al. (2008) for the Lupus and Ophiuchus cloud complexes. They found that Lupus can be nicely explained by the She & Leveque (1994) results, while Ophiuchus does not fit any of the tested turbulent models.

One further prediction by current numerical models of turbulence is the mode of star formation. Mac Low & Klessen (2004) state that the driving length of the turbulence determines if a clustered or isolated mode is predominant. Large scale driving favours the formation of clusters and small scale driving more isolated star formation. If the driving length was lower than the Jeans length, no star formation occurs, since successive shocks are too frequent. Observationally this would mean that GMCs with different modes of star formation should show a difference in cloud structure. Evidence for this has been obtained for the Orion and California Nebula clouds by Froebrich et al. (2007) and Lada et al. (2009). Both clouds show a significant difference in their structure and at the same time possess very different modes of star formation – clustered in Orion and more isolated in the California Nebula Cloud. On the other hand, Heyer et al. (2006) found more or less identical velocity structure functions for the Rosette Nebula and Maddalena's Cloud. While the Rosette forms a cluster of massive OB-stars, there is almost no star formation going on in Maddalena's Cloud.

Given the partly contradicting evidence one could ask if the turbulent velocity field and its resulting density distribution has a significant influence on the mode of star formation within a GMC. Or are there other influencing factors? In this paper we will review the possible techniques to determine the column density distributions of nearby GMCs (Sect. 2). We will then present our all-sky near infrared extinction maps and some results about the column density structure of GMCs in Sect. 3.

2. Methods to measure column density

To observationally study the structure of GMCs we need to observe the column density distribution of material - in other words the projected three dimensional distribution of the density. Only in rare cases, by using multi-wavelength observations combined with numerical modelling, is it possible to investigate the real 3D structure of clouds (as it has been done for the core ρ Oph-D by Steinacker et al. 2005). Pseudo three dimensional information can however be obtained by using radial velocity information as the third dimension.

Molecular hydrogen does not possess a permanent dipole moment. Hence, at the typical temperatures of molecular clouds it will not emit any radiation. Observations thus have to use different tracers such as dust or other abundant molecules. This naturally results in a number of possible observational methods, which will be described in the following subsections. For each of those we will briefly describe the method and its advantages and disadvantages. In most cases some examples of works using these methods are given. In order to compare them with each other, we will focus on investigations of the small starless cloud B 68.

2.1 Molecular Line Emission

At the conditions (temperature and density) of molecular clouds, emission lines from molecules are usually in the sub-mm and radio regime of the electromagnetic spectrum. In order to use them as tracer for molecular hydrogen, their abundances need to be known. These are usually very small, but sufficient amounts of radiation are emitted in the high density regions of clouds. However, it is very difficult to study low column density regions. If lines are optically thin, they are hence perfect tracers for the high density regions. Difficulties arise from the fact the abundances can vary due to chemical evolution or freeze out of molecules onto dust grains. Hotzel et al. (2002) show for example that the $C^{18}O$ abundance in B 68 does not correlate with the dust column density in the high A_V regions of the cloud. Further difficulties arise from the fact that the line fluxes are temperature dependent and lines can be optically thick.

2.2 Dust Continuum Emission

Due to the low temperatures of molecular clouds, sub-mm and millimetre wavelengths are required when observing the thermal dust continuum emission and using it as a tracer of the cloud material. Again, the fluxes are extremely temperature dependent, rendering an exact mass calculation is difficult since the line of sight temperature distribution is generally not known. Furthermore, the dust properties, in particular the dust emissivity at these long wavelengths is not known very accurately. An example of how this might influence the conversion from dust-continuum emission into column density is shown by Bianchi et al. (2003) for B 68. Nevertheless, using far-infrared data from COBE/DIRBE and IRAS/ISSA Schegel et al. (1998) determined an all sky extinction map, which is widely used as an extinction reference and particularly useful in low A_V regions away from the galactic plane.

2.3 Scattered Infrared Light

Deep near infrared observations of some molecular clouds have revealed a faint (surface brightness less than 1 MJy/sr) glow. This radiation, dubbed 'cloudshine' originates from scattered star light. The amount of light changes with wavelength and is also dependent on the clouds column density. Thus providing another possibility to map the column density of the cloud using either an empirical calibration or a numerical model of the column density vs. scattered light surface brightness relation. Since the column density can be mapped even in regions without background stars, very high spatial resolution maps can be obtained. Examples for this technique are Nakajima et al. (2003), Foster & Goodman (2006) and Padoan et al. (2006). For more details on this technique see Najajima (2010) in this issue.

2.4 Dust in Absorption

Dust absorbs and reflects starlight depending on wavelength, hence causing extinction. Crucially, in contrast to the emission, the absorption properties of the dust are temperature independent. In the near infrared the extinction can roughly be described by a power law with $A_\lambda \propto \lambda^{-\beta}$. Thus, the light of background stars appears dimmed and reddened when seen through dust. This opens up another set of possibilities to determine the column density of molecular clouds which are based on the extinction. Goodman et al. (2009) compared different column density tracers for the Perseus molecular cloud and concluded that extinction can be seen as the best, least biased column density tracer of all methods, representing the 'true' column density of the cloud best.

2.4.1 *Star Counting*

Pioneered by Wolf (1923) and Bok (1956), this method assumes a homogeneous distribution of background stars of intrinsically identical brightnesses, no interstellar extinction - just discrete clouds and homogeneous dust properties. For small fields and averaged over a large number of stars, these assumptions are valid enough to map the extinction for small clouds. On larger scales the change of the background star density with position has to be accounted for. The star count method usually achieves only moderate spatial resolution and is rather noisy. Nevertheless, extinction maps along the entire galactic plane have been determined by Dobashi et al. (2005) (using the Digitized Sky Survey I data) and Froebrich et al. (2005) (using the 2MASS catalogue). Optical star counts have also been used by Cambrésy (1999) to determine the structure of a number of nearby GMCs.

2.4.2 *Colour Excess Methods*

The reddening of stars, the colour excess, is the most powerful tool to determine the extinction of a cloud, as it assumes that the additional (excess) stellar colour is solely caused by the reddening due to dust and hence proportional to the column density. This method is in particular useful in the near-infrared. Not only are the colours of stars almost independent of spectral type, but the generally lower extinction allows one to probe even very highly extincted regions. The Near Infrared Colour Excess method (NICE) has been introduced by Lada et al. (1994). It is much less noisy compared to star counting but still only of moderate spatial resolution. Improvements of the method for multi-band photometry have been done by Lombardi & Alves (2001), which obtain higher signal to noise ratios by optimising the available colour information. Combining the near-infrared multi-band data with mid-infrared data e.g. from Spitzer can lead to detections of A_V values as high as 100 mag (e.g. Román-Zúñiga et al. 2009).

2.4.3 *Combined Methods*

Naturally one can combine both methods to optimise the signal to noise further by including all available information. After initial simultaneous use of star counts and colour excess by Cambrésy et al. (2002) both methods have been optimally combined by Lombardi (2005). Finally it should be noted that star counts and colour excess methods which use the mean colour of stars will measure a column density which is lower than the real column density. This difference depends most notably on the extinction and the distance of the cloud. As a result of which the measured column density distribution within a cloud changes, depending on the distance. Using colour excess methods with the median colour eliminates this distortion effect (Froebrich & del Burgo 2006).

3. Results from our All-Sky Extinction Map

In order to investigate the column density structure of all major nearby molecular clouds we have selected to apply the NICE method to the 2MASS dataset. We also selected to perform the extinction mapping using the median colour of stars to avoid non-linear, distance dependent distortion of the column density distribution. Furthermore, we determined extinction maps at four different spatial scales, separated by a factor of two each, to investigate the structure of the clouds at different physical scales. This also allows us to directly compare the column distribution of clouds at the same physical scale. All the basic calibration procedures for the maps are identical to what has been presented in Rowles & Froebrich (2009)[1].

We then investigated the structure of all nearby clouds with reliable distance estimates. This has been done by fitting an log-normal column density

[1]All our maps can be downloaded from http://astro.kent.ac.uk/extinction/index.html

distribution to the data, determining the slope γ in a $\log(N)$ vs A_V diagram, where N represents the number of pixels at a given A_V value, or determining the slope δ in a diagram showing the mass in the cloud at extinction values lower than A_V. All these investigations have been done for the four different spatial scales in each cloud if possible (in some cases the map with the largest spatial scale did not have enough pixels for the analysis).

In general we find a change in γ and δ with the spatial scale (resolution) we use in our maps. In the majority of clouds γ and δ decrease with increasing spatial scale. This is most likely simply an observational effect. Due to the increased spatial scale, small scale high extinction regions are not detected anymore, and hence the slopes γ and δ become steeper. Our approach hence allows us to directly compare the γ and δ values of the clouds with each other, since we can correct for this effect. We choose 0.1 pc as the spatial scale for all our calculations, since all clouds are 'observed' in our maps with such a spatial resolution. A simple linear interpolation was used to obtain the γ and δ values for each cloud at 0.1 pc. This, together with the use of the median colour excess, allows us for the first time to compare the column density distributions of nearby GMCs without any observational bias.

In the majority of clouds the $\log(N)$ vs A_V and the accumulated mass diagram cannot be fit by a single straight line, i.e. is not represented by a single power law. Rather two different regimes are found. There is a low A_V regime which usually possesses a steeper slope than the high A_V region. Assuming that the distribution of material at low column densities is entirely determined by the large scale turbulent motions, naturally a power law distribution is expected due to the self-similar nature of the turbulence. At higher column densities self-gravity can become important and will hence alter the distribution. The column densities or A_V values where this is the case can be considered the extinction threshold for star formation. This has first been noticed by Johnstone et al. (2004), who found no dense cores in Ophiuchus in regions with an extinction below 7 mag of optical extinction. Typical values for all clouds we investigate in our map are 4-8 mag A_V.

We can further compare the slopes γ and δ for the high and low A_V regions for all investigated clouds. In particular for the accumulated mass diagram there is a trend. Typical values for δ in the low A_V region are -0.2 to -0.4, while in the high A_V region values range between -0.1 and -0.2 (see Fig. 1). The important thing to note here is, that the scatter in the low A_V region is significant, i.e. including the uncertainties, the δ values for different clouds are different. Hence, we find detectable differences in the distribution of the low column density material within those clouds. They might be caused by different sources for the turbulence. In contrast to that, the δ values for the high column density, star forming parts of the clouds are indistinguishable. The only exception to this is the California Nebula cloud. Hence, once gravity

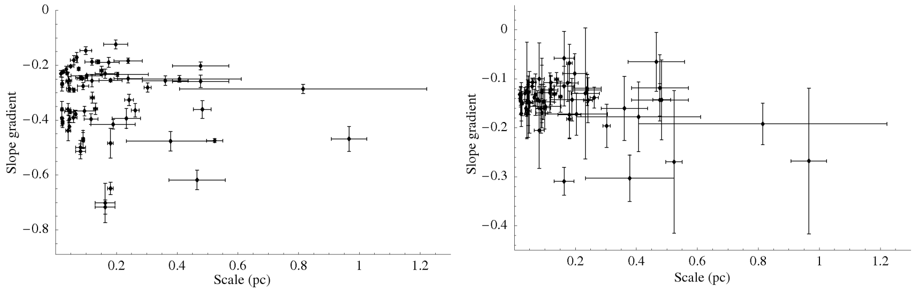

Figure 1. Distribution of the slopes δ for all investigated GMCs at different scales for the low (**left**) and high (**right**) A_V regime.

becomes the determinant force, the column density distribution in the clouds seems to be, at least on the scale of 0.1 pc, independent of the surrounding conditions.

Finally we can compare the masses contained in the high and low A_V regions in the cloud. This gives an indication of how much of the total mass of a cloud is currently involved in the star formation process. If we assume that about 1/3 of this mass is actually converted into stars (Alves et al. 2007), then we can estimate the overall star formation efficiency of all GMCs. We find that the values range from a few to a few tenths of a percent.

As a next step we will determine the structure function of all our clouds and compare them to predictions from turbulent models (Kolmogorov 1941; She & Leveque 1994; Boldyrev 2002) to investigate which clouds can be explained (if at all) by which model. We will then be able to combine these findings with our other structure analysis and knowledge about the star formation mode and activity in each cloud to investigate any possible reasons for the different star formation modes in the clouds.

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