WARM MOLECULAR CLOUDS

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Abstract. Warm molecular gas is important in a large range of astronomical contexts. We discuss here determinations of the temperature and mass of warm material in protostellar disks and cores, photon dominated regions, and molecular material shocked by protostellar outflows. We then compare these results to heating and cooling models. The models of dense cores and photon dominated regions are not adequate to explain the large amounts of warm material observed. This conclusion raises the possibility that there may be other heating mechanisms at work in these regions which theorists have not yet included in their models.

1. Introduction

Warm gas (at 100 K $\lesssim$ T $\lesssim$ 4000 K) exists in molecular clouds on a wide range of size scales with a variety of excitation mechanisms. The gas appears in disks and dense cores surrounding young stars or their accompanying ultracompact HII regions. Photon–dominated regions (PDR's) and recently shocked clouds also contain warm molecular material. On a global scale, warm gas may be the primary molecular component in the inner regions of starburst and other types of active galaxies. Emission from the warm gas usually reflects the presence of strong radiative or mechanical heating sources and traces the effect of these sources. The warm gas is important observationally since, when present, it often dominates the appearance of a region in many lines and the continuum, even if it accounts for only a fraction of the mass. The high temperatures in this gas also permit gas–phase and gas–grain chemistry to differ significantly from the chemistry in cool quiescent clouds. Other reviews in this volume discuss the chemistry and physics of the warm regions. I will summarize here the current observational results on the temperatures and amounts of warm material in the different kinds of regions. We can then compare the results to heating and cooling models to see if these models are adequate to explain the observed properties of the regions.

The simplest method for determining the kinetic temperature of a cloud employs measurements of the brightness temperature, T_{MB} of an optically thick line. For warm clouds, measured in appropriate transitions, the observed T_{MB} is equal to the kinetic temperature of the optically thick gas times the area filling factor of the cloud. A more widely useful method makes use of optically thin emission in several lines arising from different states of the same molecule. A model taking into account both the collisional and radiative excitation of the states and the effects of radiative coupling can be used to derive the relative populations in the measured states and also the kinetic temperature in the cloud. Abundant linear rotors, especially CO,

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are a frequent choice for temperature determinations using relative state populations. One can overcome problems with high opacity by using a rare isotopic variant of CO. In cases where there is a background continuum source, one can determine the populations of many levels at once using the infrared ro-vibrational transitions. In some sources where density dependent non-LTE population effects are important, it may be possible to use ro-vibrational absorption lines of molecules without permanent dipole moments like H_2 and C_2H_5 to determine the temperature.

Symmetric top molecules like methyl cyanide offer access in the millimeter band to a large number of states at a range of energies above ground, all at similar frequencies. Transitions arising from the same rotational state in different K ladders offer a relatively density–independent means of estimating kinetic temperatures. Molecules like CH_3CN suffer, however, from being difficult to excite and not very abundant.

2. Observations of Disks and Cores

The regions surrounding protostars and young stellar objects often include warm molecular components. Closest to the stellar objects are extremely warm (T$\sim$3500 K), dense (n$\sim$$10^{10}$ cm^{-3}), zones producing emission in the 2 μm vibrational overtone bands of CO. In low to moderate luminosity regions, $\sim$25% of the sources searched show such emission (Carr 1989). More luminous sources also have detectable CO overtone emission (Scoville et al. 1979, Geballe and Persson 1987), but higher dust opacities may conceal the emission regions in many of these sources. The total masses of the emission regions are small (a few 10^{-8} to a few 10^{-6} $M_\odot$). A number of heating mechanisms including accretion luminosity and shocks due to infalling matter seem possible as explanations of the observed emission (Scoville et al. 1983, Carr 1989).

Multi-transition millimeter and submillimeter line studies of cores around newly formed luminous stars imply that these regions contain substantial amounts of dense, warm gas. Observations of CS toward regions containing ultracompact HII regions and/or H_2O masers show that there is typically 30-300 $M_\odot$ of material at densities of $10^{5.5}$ to $10^{6.5}$ cm^{-3}(Cesaroni et al. 1991, Plume 1991). NH_3 and CH_3CN observations yield temperatures for the dense material of 120-300 K (Mauersberger et al. 1986, Güesten and Fiebig 1988, Churchwell, Walmsley and Wood 1991, Mangum 1991).

What heats the warm gas in dense cores? The linewidths in the regions are similar to those in other quiescent clouds (ΔV $\sim$5 km s^{-1}), making shock excitation unlikely. Are gas-grain collisions a plausible heating mechanism in these cores? Radiative transfer models of dense cores with a central luminosity source and a surrounding cavity show a hot layer at the inside where primary radiation strikes the cloud. Once outside of this layer, the dust temperatures are, at best, slightly below the unattenuated equilibrium temperature of the grains. The models predict dust temperatures of only $\sim$50 K at the typical $\sim$$10^{17}$ size of the dense cores discussed here (Egan, Leung, and Spagna 1988, Butner et al. 1990). As a consequence, the source of the high gas temperatures in these cores remains unclear.

3. Photon Dominated Regions

The edges of clouds illuminated by far-ultraviolet radiation contain a layer of warm molecular gas. Models of the PDR's explain the temperature as the result of a balance of heating by electrons photoejected from grains and collisionally de-excitation of photo-excited high-v H_2 with cooling through O^o and C^+ fine structure lines, CO rotational lines, and gas-dust collisions (Tielens and Hollenbach 1985, Black and van Dishoeck 1987, Sternberg and Dalgarno 1988). At high densities, the models predict gas temperatures of several hundred K into the cloud to a column depth of $\sim 10^{21}$ cm^{-2}. Model temperature profiles agree well with the observations of the v=(0–0) rotational transitions of H_2 in the Orion Bar PDR (Parmar, Lacy, and Achtermann 1991). In addition, the models succeed in accounting for observations of strong emission in ro-vibrational H_2 lines arising in states with v=1 in sources that also show the emission in the higher v lines which is characteristic of fluorescence. Sternberg and Dalgarno (1989) conclude that the high temperature region necessary to produce the v=1$\rightarrow$0 radiation arises from heating by collisional de-excitation of the higher vibrational states of H_2.

The theoretical models are somewhat less successful at explaining the high-J CO emission from PDR's. Observations of ^{12}CO imply column densities of > a few 10^{21} to 10^{22} cm^{-2} in H_2 of gas at 100–300 K, substantially higher than the observed dust temperatures. Models with high density clumps come close to satisfactorily accounting for this emission (Burton et al. 1990). However, more recent observations of ^{13}CO 6$\rightarrow$5 implies that there are even larger column densities (a few 10^{22} cm^{-2}) of H_2 at temperatures $\gtrsim$100 K in some regions where T_{dust} is not high enough for dust-gas heating to be effective (Graf et al. 1990).

4. Shock Heated Gas

In the cores of molecular clouds, high velocity protestellar winds are the ultimate source of the most prominent shock-heated material. The material cooling behind the shock in the best-studied region, Orion/KL, ranges in temperature from several thousand K down to only $\sim$2 times the temperature of the ambient cloud (i.e., to 150–200 K). In the Orion region, models variously explain the line intensities of the numerous near-IR ro-vibrational transitions of H_2 as arising in gas affected by a C-shock, where the magnetic field drags along the ions and moderates the usual shock dicontinuites (Draine, Roberge, and Dalgarno 1983) and as arising in a pure J-shock (Brand et al. 1988). Each of these models has its own problems and advantages (see Hollenbach, Chernoff, and McKee 1988). The recent suggestion that one can combine both C and J shocks if the shocked material lies along a bow-wave on the leading edge of a supersonic gas clump offers some promise as a

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means of accounting for the observed emission in H_2 (Smith, Brand, and Moorhouse 1990).

Observationally, one of the big problems in studying the shocked protostellar regions has been that the best diagnostic lines- the near-IR H_2 lines and the far–IR and submm lines of CO– have not given us information about the same region within the shock. The H_2 lines almost all arise in gas at temperatures in excess of 1500 K while the temperatures derived from the CO observations are significantly lower. It has never been very clear how to de–couple the possible effects of excitation, chemistry, and extinction when comparing H_2 and CO observations. Observations of lower excitation H_2 pure rotational lines (Parmar et al. 1991) indicate that the differences between earlier H_2 and CO measurements were dominated by excitation. The 0-0 J=4-2 and 3-1 line observations of Peak 1 in Orion give a H_2 column density of 3×10^{21} and a temperature of 500 K (Parmar et al. 1991). A temperature of 750 K and a very similar column density provide the best fit to the far-IR CO lines (Watson et al. 1985), while the submm CO data require somewhat lower temperatures and higher column densities. The cooling post-shock gas in both C and J shock models with reasonable parameters can have sufficient column density at the appropriate temperature to explain the observations.

Emission from warm, post–shocked gas is more widespread and prominent than previoiusly thought. In very luminous star formation regions, high velocity gas dominates the emission in the CO J=7→6 line (Jaffe et al. 1989). Even in the well– studied Orion region, recent CO J=2→1 mapping implies that there is high velocity molecular emission present on scales of ~1 pc, covering an area as much as 100 times larger than previously believed (Martin-Pintado et al. 1990).

5. Conclusions

There is warm (T$\gtrsim$100 K) gas present in many types of molecular clouds. The theoretical understanding of the thermal balance in the warm gas is, in general, quite good, but there are several problems : In dense cores, the large sizes and high column densities of the warm regions implied by the multi-transition studies are inconsistent with the likely heating by dust–gas collisions. In photon–dominated regions, the large columns of ~100 K gas implied by the ^{13}CO 6→5 results are not compatible with current models for such regions. The fundamental problem in both cases is that the observed column densities are too large for primary stellar radiation to be effective. There is a strong possibility that we have failed to include some significant heating mechanisms in models of the regions. An additional but somewhat different puzzle arises when trying to explain the source of the widespread warm, dense, high velocity gas observed in many regions.

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