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The Monoceros OB1 Dark Cloud: A Comparison of ^{13}CO, C^{18}O, and CS Observations of Outflow Regions

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We compare ^{13}CO and C^{18}O J=1→0 observations of four massive outflows in the Mon OB1 dark cloud with CS J=2→1 (Wolf-Chase, Walker, & Lada 1995; Wolf-Chase & Walker 1995) and CO J=1→0 (Margulis, Lada, & Snell 1988) observations. We find the ^{13}CO J=1→0 transition to be optically thin almost everywhere and derive a ^{13}C^{16}O/^{12}C^{18}O abundance ratio of $\sim$ 8.1. Comparison of ^{13}CO and CS column densities in the line cores indicates that the relative CS abundance may be enhanced by a factor of two to four over the typical abundance in quiescent clouds. However, comparison of the column densities derived from the outflowing gas in the line wings indicates the CS abundance may be enhanced by one or two orders of magnitude in these regions. The CS abundance is correlated with the mechanical luminosity of the outflows, suggesting a possible correlation of CS abundance with the strength of the shocks where the wind impacts the ambient cloud material. The CS abundance is about an order of magnitude higher in the redshifted outflowing gas than in the blueshifted outflowing gas. We speculate this may be due to the higher velocities observed in the redshifted gas associated with these outflows.

INTRODUCTION

There has been much debate on whether the relative abundances of certain molecular species are enhanced in shocked regions (eg. Hartquist, Oppenheimer, & Dalgarno 1980; Takano 1986; Thronson & Lada 1984; Walker et al. 1990). In this paper, we investigate the relative abundance of CS in four massive outflow regions in the Mon OB1 dark cloud. Margulis, Lada, & Snell (1988) (hereafter MLS88) conducted an unbiased CO J=1→0 survey for outflows over a large portion of the cloud previously mapped by Blitz (1978). They discovered and mapped 9 distinct outflows in the surveyed region. Four of these 9 outflows only showed evidence for high-velocity redshifted gas. Wolf-Chase, Walker, & Lada (1995) (hereafter WWL95) searched for CS J=2→1 emission in the vicinities of all the outflows and IRAS sources in Mon OB1. They found strong CS J=2→1 emission in the vicinities of the 4 most massive CO outflows (B, C, D, & H, using the nomenclature of MLS88), and weak or no CS emission elsewhere. Wolf-Chase & Walker (1995) (hereafter WW95) found that $\geq$20% of the total CS emission is associated with gas entrained in the outflows. Most of this gas lies at velocities within the cores of the CO lines. Their results suggest that (1) dense cores are required for the production of massive outflows, (2) densities are enhanced in a "snow plow" effect as outflows sweep-up material in shells as they evolve, (3) CS abundances are enhanced in shocks where outflows impact the ambient cloud, or (4) some combination of these effects. In this paper, we determine the relative abundance of CS in the outflow regions by comparing CS (and $C^{34}S$) column densities in these regions with column densities derived from ^{13}CO and $C^{18}O$ J=1$\rightarrow$0 observations acquired at the NRAO 12m telescope. The ^{13}CO and CS linewidths are similar in this cloud, enabling a direct comparison of the amount of material in the line wings.

Relative CS Abundance in Outflow Regions

Columns 2 - 4 of Table 1 list the velocity integration ranges for the blue- and redshifted CO outflow gas, the CO outflow dynamical timescale, and the CO outflow mechanical luminosity (MLS88). Columns 5 & 6 list the velocity integration ranges chosen for the CS (WW95) and ^{13}CO data, and the relative CS enhancement in the blue- and redshifted outflow gas (determined from the ratio of H_2 column densities calculated from CS, $C^{34}S$, and ^{13}CO data). The relative CS abundance enhancements appear to correlate with the outflow mechanical luminosities. Additionally, the enhancements are greatest in the redshifted outflowing gas. In outflows C, D, & H, the intensity of the CS red wing is enhanced relative to the ^{13}CO red wing (fig. 1). Otherwise, the CS and ^{13}CO spectra have a somewhat similar appearance. Column densities were not calculated from the CS line wings in outflow H, or for the redshifted CS gas in outflow B, due to the relatively low intensities of the CS wings in these sources. The CO spectra indicate material moving at higher velocities in the redshifted gas than in the blueshifted gas. If the sources powering these outflows are located such that the blueshifted gas is impeded by denser foreground gas, this might explain why there is little blueshifted gas at velocities high enough to be seen as line wings in CO for sources B & C. Since the driving source for outflow C, Allen's star (Allen 1972), is a deeply embedded object ($A_v \geq 26$ mag), it is reasonable that this may be the case. Conservation of momentum would require that the more mass swept-up, the slower the outflow. This scenario is suggested by the observation of blueshifted CS (and ^{13}CO) gas at velocities within the line cores of the CO gas. The CO outflow mechanical luminosity is also greater for the redshifted gas, since there is a larger mass distribution at *higher* velocities than in the blueshifted gas.

WWL95 found that CS linewidths are approximately 30% broader near the outflow lobes than on the line-of-sight toward IRAS sources associated with these outflows. They also found that clumps of CS (identified from velocity channel maps of Wolf 1992) could be identified with the outflow lobes. We find the ^{13}CO and $C^{18}O$ linewidths to be $\sim$ 10 - 20% broader near the outflow lobes associated with outflows C & D, but find no noticeable difference toward outflows B & H. This is probably related to the higher mechanical luminosities of outflows C & D. Likewise, clumps of ^{13}CO and $C^{18}O$ can be identified with outflow lobes, and velocity centroid plots over the ^{13}CO and C^{18}O line cores in the vicinity of the largest outflow (D) suggest that the outflowing gas dominates the cores of these lines (Wolf-Chase 1995). The ^{13}CO and C^{18}O observations suggest that the presence of CS gas in the vicinity of the four most massive outflows in Mon OB1 is related both to density and chemical enhancements in these regions. The high-velocity CS emission may arise from dense clumps of shocked gas entrained by jets driving the outflows. Possibly, the relative CS abundance is more enhanced in the redshifted gas because of the higher-velocity shocks involved. The lower-velocity emission in the CS line cores may arise, at least in part, from dense material swept up at the periphery of the outflow. Higher resolution observations are required to verify this. The fact that CS enhancement appears to be correlated with outflow mechanical luminosity suggests a similar interpretation to that of Tafalla & Bachiller (1995) regarding NH_3 observations of the bipolar outflow L1157: There is much dense gas in the path of the winds associated with the four massive outflows, and much of the CS emission arises from shocked material where the wind impacts the ambient cloud. Tafalla & Bachiller (1995) suggested this was true for the youngest outflows. We suggest that the critical factor is the mechanical luminosity (which also depends on age for individual outflows). Outflow D is one of the oldest outflows in Mon OB1, but is being driven by a relatively high-luminosity source embedded in an extended core of dense gas.

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Table 1
CO Outflow Parameters and Relative CS Enhancement

Outflow	ΔV^a_{CO} blue, red (km s^{-1})	τ^a_d (yrs)	L^a (L$_\odot$)	$\Delta V_{CS,^{13}CO}$ blue, red (km s^{-1})	$\frac{NH_2(CS)}{NH_2(^{13}CO)}$ blue, red
B	..., 10-16	4.2×10^4	.44	4-6, ...	2, ...
C	..., 12-22	1.1×10^4	25	3-6, 10.5-15	10, 164
D	-10-2, 11-21	6.9×10^4	11	2-4.5, 6.5-10	2, 19
H	0-3, 10-30	1.2×10^4	8.2	..., ...	2^b

[a] From MLS88
[b] Ratio of total column densities derived from line cores

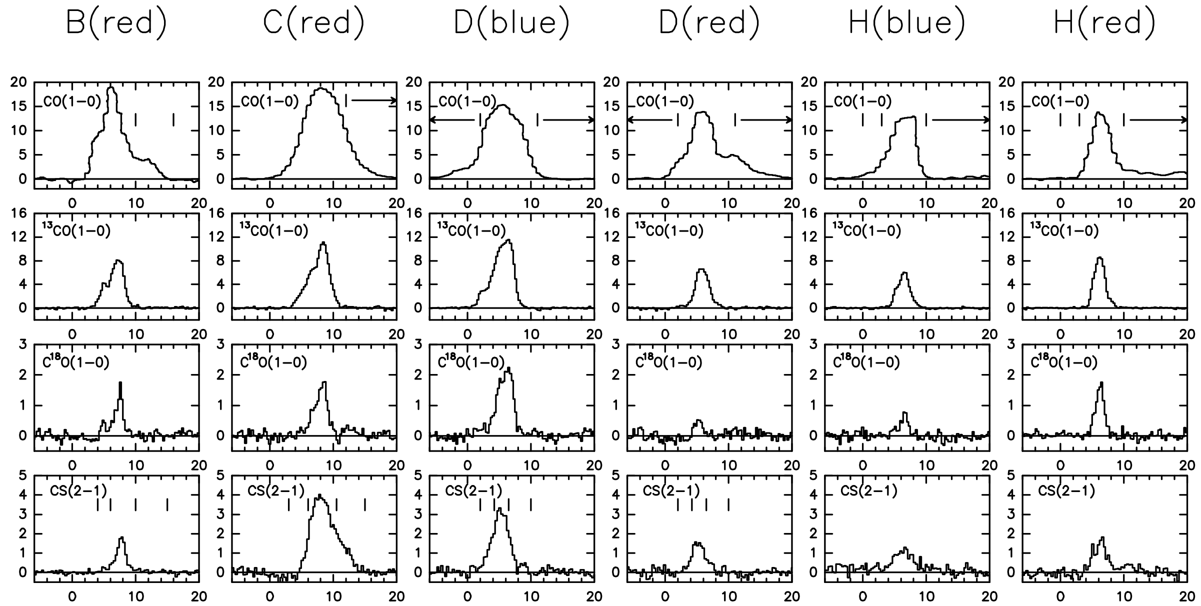

Figure 1. Comparison of CO J=1→0, ^{13}CO J=1→0, C^{18}O J=1→0, & CS J=2→1 spectra (rows 1, 2, 3, & 4, respectively) at the positions of maximum CO wing integrated intensity for outflows B, C, D, & H. Outflow integration limits for the CO and CS spectra are indicated with vertical lines. CO spectra are taken from MLS88; CS spectra are taken from WW95.