

OBSERVATION OF [C I] TOWARD THE GL 2591 AND W28 A2 MOLECULAR OUTFLOWS

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ABSTRACT

Molecular outflows associated with GL 2591 and W28 A2 were observed in the 492 GHz [C I] line. Upper limits are set on the [C I] emission in the extremely high velocity line wings. These limits are discussed in terms of wind-driven and jet-driven models of molecular outflows.

Subject headings: ISM: atoms — ISM: individual (GL 2591, W28 A2) — ISM: jets and outflows — ISM: kinematics and dynamics

1. INTRODUCTION

Recent observations of molecular outflows in star-forming regions have revealed that, in addition to the usual high-velocity ($5 \lesssim |V - V_0| \lesssim 20 \text{ km s}^{-1}$, hereafter HV) outflows, many sources show extremely high velocity ($|V - V_0| \gtrsim 20 \text{ km s}^{-1}$, hereafter EHV) wings on CO lines (Koo 1989; Masson, Mundy, & Keene 1990; Bachiller & Cernicharo 1990; Bachiller et al. 1990; Chernin & Masson 1992; Choi, Evans, & Jaffe 1993). The EHV CO emission could arise in the stellar wind, or it could be ambient molecular gas which has been entrained (Bachiller & Go'mez-Gonzalez 1992).

Choi et al. (1993) considered the idea that the EHV emission arises from CO in the stellar wind. Their assumption was that the HV CO outflow is driven by the EHV CO outflow and that the momentum is conserved in this process. They found that the amount of EHV CO was consistent with this hypothesis only for low-luminosity sources. To explain the deficit of EHV CO in sources with higher luminosity, the fraction of C in CO would have to decrease with source luminosity or rate of production of ionizing photons. This trend would be plausible if the missing C were in the form of C^0 or C^+ , as indicated by models of chemistry in winds (Glassgold, Mamon, & Huggins 1991). While EHV wings on lines of C^+ would be difficult to detect, a search for EHV wings from C^0 is more tractable (Choi et al. 1993).

Walker et al. (1993) observed the [C I] fine structure line at 492 GHz toward about a dozen molecular outflow sources and showed that the C^0 abundance in the HV outflow is comparable to that in the ambient cloud. Their velocity coverage and noise level were not sufficient to detect EHV wings. If the EHV outflow is not swept-up material, the C^0 abundance in the EHV outflow is not necessarily the same as in the ambient cloud. In this paper, we present low-noise observations of the GL 2591 and W28 A2 molecular outflows in the 492 GHz [C I] line. For these two sources, only $\sim 1\%$ and $\sim 5\%$ of the carbon can be in the form of CO if the EHV CO wings are caused by gas in the stellar winds (Choi et al. 1993). If most of the carbon

in the wind is in the form of C^0 , EHV wings should be readily detectable in these sources.

Recently, outflow models involving collimated jets have been suggested (Stahler 1993, 1994; Masson & Chernin 1993; Raga et al. 1993). In Stahler's picture, gas is entrained in a turbulent mixing process, producing a continuous range of velocities from the ambient gas velocity to velocities near the maximum of the HV flows ($15\text{--}20 \text{ km s}^{-1}$), but his model does not yet include specific predictions for higher velocities. Masson & Chernin (1993) address the origin of discrete EHV features by bow shocks where jets encounter the ambient gas but do not specifically address smooth extended emission like the EHV wings. Since Masson & Chernin invoke a wandering jet to produce multiple EHV features, we assume that smooth extended wings may be the superposition of many such features. While specific predictions of either CO or [C I] in EHV wings are not available for these jet models, we will argue in § 4.2 that EHV [C I] wings would probably not be detectable.

2. OBSERVATIONS

We observed GL 2591 on 1993 June 20 and W28 A2 on 1993 May 18 and 19 with the 10.4 m telescope of the Caltech Submillimeter Observatory (CSO)⁵ at Mauna Kea. We observed at one position in each source given in Table 1, the peak position of the EHV CO outflow (Choi et al. 1993). The data were obtained using a 492 GHz SIS receiver (Walker et al. 1992) in double-sideband mode with a 500 MHz AOS as the spectrometer. The antenna temperature (T_A^*) was calibrated by the standard chopper-wheel method, which automatically corrected, to first order, for the effects of atmospheric attenuation. The beam size (FWHM) was about $15''$, and the main beam efficiency (η_{mb}) was about 0.53 (Phillips 1993). We present our data in terms of $T_R = T_A^*/\eta_{\text{mb}}$.

To evaluate the quality of the baseline, the data were taken by position switching with two OFF positions in a symmetric pattern: ON \rightarrow OFF1 \rightarrow OFF2 \rightarrow ON \rightarrow ON \rightarrow OFF2 \rightarrow OFF1 \rightarrow ON. The position offsets of the two OFF positions are shown in Table 1. To check for contamination in the OFF positions and systematic errors in the baseline, we reconstructed difference

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TABLE 1
 SOURCE PARAMETERS

SOURCE	α_{1950}	δ_{1950}	OFF1 ^a		OFF2 ^a		NOISE ^b (K)	BASELINE INTERVALS (km s ⁻¹)
			$\Delta\alpha$	$\Delta\delta$	$\Delta\alpha$	$\Delta\delta$		
GL 2591	20 ^h 27 ^m 34 ^s .9	40°01'09"	-120"	120"	120"	-120"	0.062	(-70, -50) and (30, 50)
W28 A2	17 ^h 57 ^m 26 ^s .8	-24°03'54"	0"	120"	0"	-120"	0.41	(-120, -80) and (80, 100)

^a Coordinates of OFF positions relative to the central position.

^b Root mean square of noise in the T_R scale with a velocity resolution of 0.7 km s⁻¹.

spectra of the OFF positions by regarding OFF1 as the ON position and OFF2 as the OFF position. Since the difference spectrum has only half the integration time of the ON spectrum, its rms noise level is higher than that of the ON spectrum by a factor of about (2)^{1/2}.

The difference spectrum for GL 2591 (Fig. 1, *bottom panel*) shows weak emission at the line core and inner blue wing. In the outer wings, however, the difference spectrum is quite flat. The difference spectrum for W28 A2 (Fig. 2, *bottom panel*) does not show any emission above the noise level. These spectra indicate that the limit on weak lines is set by the noise in the ON spectrum, rather than by baseline effects.

For each spectrum, a first-order baseline was removed. The last column of Table 1 shows the velocity intervals considered in the baseline determinations.

3. RESULTS

Our main goal is to test the picture in which a stellar wind at velocities of ~ 100 km s⁻¹ drives the molecular outflow at $|V - V_0| \lesssim 20$ km s⁻¹ by sweeping up ambient gas, conserving momentum. Therefore, we first discuss our results in terms of this picture, but we also address jet-driven outflows in § 4.2.

The limits on [C I] in the wind set by our spectra are quite severe. We have calculated the [C I] emission in the EHV wing predicted by the following assumptions: the mass-loss rate is derived from the HV outflow using momentum conservation; all the missing carbon in the EHV wind (i.e., carbon not detected by the CO observations) is in the form of C⁰ (hence our prediction is an upper limit); the EHV CO traces the velocity field of the wind; and the temperature is much higher than 62.5 K, corresponding to the energy needed to populate the highest level in the fine structure triplet. The results are not

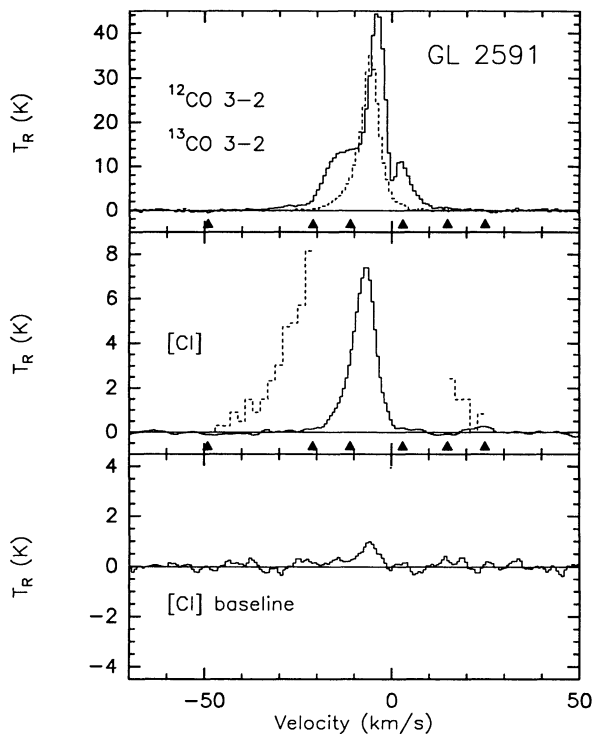


FIG. 1.—[C I] spectrum of GL 2591 with a first-order baseline removed (*middle panel*). For comparison, CO and ¹³CO $J = 3 \rightarrow 2$ spectra taken toward the position of the infrared source are shown in the top panel (see the map in Choi et al. 1993 for details). The dashed spectrum in the middle panel is the [C I] line predicted from the CO $J = 3 \rightarrow 2$ line (see text). Filled triangles below the baseline of the [C I] and CO spectra are the CO $J = 3 \rightarrow 2$ wing boundaries given in Choi et al. (1993). The bottom panel shows a difference spectrum of the OFF1 and OFF2 positions.

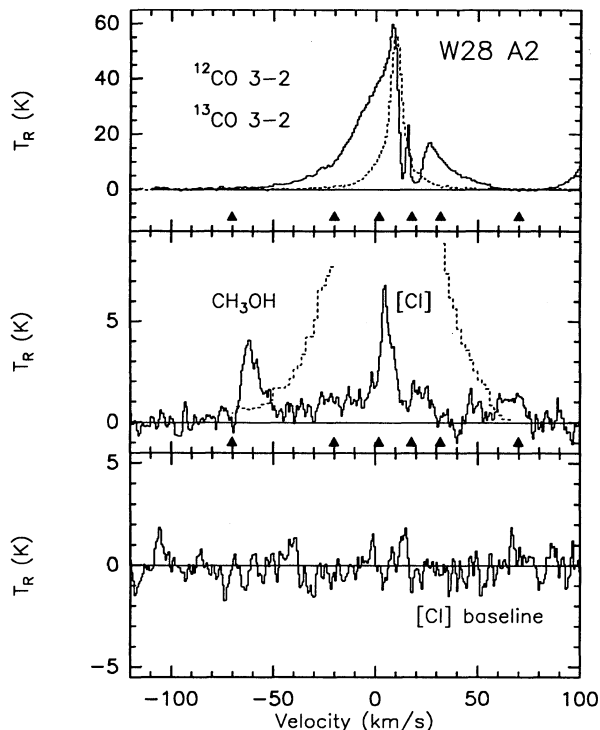


FIG. 2.—[C I] spectrum of W28 A2 with a first-order baseline removed (*middle panel*). For comparison, CO and ¹³CO $J = 3 \rightarrow 2$ spectra are shown in the top panel. The dashed spectrum in the middle panel is the [C I] line predicted from the CO $J = 3 \rightarrow 2$ line (see text). Filled triangles below the baseline of the [C I] and CO spectra are the CO $J = 3 \rightarrow 2$ wing boundaries given in Choi et al. (1993). The bottom panel shows a difference spectrum of the OFF1 and OFF2 positions.

very sensitive to the last assumption, as long as the temperature is not very low.

3.1. GL 2591

Our [C I] spectrum of GL 2591 (Fig. 1) agrees with that of Walker et al. (1993) though their position was about 10" east of ours. We failed to detect EHV [C I] wings, even though our noise is about 4 times lower and our velocity coverage is 10 times wider than that of Walker et al. (1993). Figure 1 also shows CO lines taken from about 10" east of the [C I] observation position. The line profiles of [C I] and $^{13}\text{CO } J = 3 \rightarrow 2$ lines agree very well, which implies that there is no enhancement of atomic carbon abundance in either the HV or EHV outflows if both lines are optically thin.

The limit on EHV wings is $T_R < 0.1$ K, except near 25 km s^{-1} , where there is a possible (about 3σ) feature. The predictions exceed the detection limit by factors ranging from 3 to 80 for the blue wing and 8 to 24 for the red wing.

3.2. W28 A2

Our [C I] spectrum of W28 A2 is shown in Figure 2. This source was not observed by Walker et al. (1993). As in Figure 1, we also show the CO and $^{13}\text{CO } J = 3 \rightarrow 2$ lines in the same direction, as well as the spectrum of the OFF position. In this source, the noise is higher, and we set a limit of about 1 K on the weakest wing we could have detected. This limit is still much lower than the level of predicted lines. The blue EHV wing contains a distinct peak between -70 and -50 km s^{-1} , but this peak coincides with a line of $\text{CH}_3\text{OH } (J_{K_1, K_2} = 4_{11} \rightarrow 3_{01})$ at a rest frequency of 492.1607 GHz, which appears to be prominent in this source, but not in GL 2591. If we ignore the region of CH_3OH emission, we still set interesting limits on the [C I] emission. At the boundaries between inner and outer wings, the predicted emission is 7 to 9 times our detection limit.

4. DISCUSSION

4.1. Wind-driven Molecular Outflow Models

Our failure to detect [C I] emission in the EHV wings at levels far below the predictions implies that some of the assumptions used to make the predictions must be incorrect. First, we note that the predictions are not very sensitive to temperature, unless the temperature becomes very low (< 10 K), and our analysis of the CO EHV emission yielded lower limits to temperatures which were 16 K for GL 2591 and 94 K for W28 A2, with the temperatures likely to be considerably higher. One explanation for not detecting EHV [C I] emission is that most of the carbon is ionized, even though most hydrogen may be in the form of H^0 . Some calculations of winds from protostellar disks conclude that the carbon will be ionized (Safier 1993). Detection of EHV wings in the [C II] line, while difficult, may be possible. If we make predictions of [C II] emission with the same assumptions in the second paragraph of § 3 with C^+ instead of C^0 , the [C II] intensities at the boundaries between inner and outer wings would be $1\text{--}4 \times 10^{-11} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ Hz}^{-1}$ for GL 2591 and $3\text{--}4 \times 10^{-11} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ Hz}^{-1}$ for W28 A2. Assuming we need to detect a level of $1 \times 10^{-11} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ Hz}^{-1}$ to clearly demonstrate EHV wings, this would translate to a $T_A^* = 1.0$ K, assuming a filling factor of 0.2, based on the maps of the EHV wings in CO (Choi et al. 1993), and an efficiency of 0.6 for a heterodyne instrument on the Kuiper Airborne Observatory (Boreiko, Betz, & Zmuidzinas 1990). Using the instrumental

parameters described by Boreiko & Betz (1991), we calculate an rms noise of 0.23 K would be reached in 1000 s of integration with the 20 MHz (3 km s^{-1}) filters. So far, no observations of these sources in the [C II] line are available (Betz 1994).

We have assumed that the carbon in the wind must be in one of three forms (CO , C^0 , or C^+) based on models of wind chemistry that show all other molecules containing carbon to be completely negligible (Glassgold et al. 1991). These authors also argue that dust, if it forms at all, will form outside the region of molecule formation and will be silicates, rather than carbon grains. While these chemical models were developed for winds from lower mass stars, these basic properties seem quite robust.

Another possible explanation is that the wind is mostly at velocities much higher than are traced by the EHV CO, producing wider and weaker wings. For example, Mitchell et al. (1989) detected a CO ($v = 0\text{--}1$) wing as wide as $\sim 130 \text{ km s}^{-1}$ from GL 2591. As discussed by Choi et al. (1993), very wide wings would have been difficult to detect in a CO emission line; they are even harder to detect in [C I]. For GL 2591, our velocity coverage is $\sim 150 \text{ km s}^{-1}$ on each side of the [C I] line, so any wing wider than that could not be distinguished from the baseline. For W28 A2, it is impossible to detect a wider wing because a CH_3OH line on the blue side and a very bright H_2CO line on the red side (outside the velocity range plotted in Fig. 2) contaminate the baseline. If we assume a square-shaped wing with a terminal velocity of 300 km s^{-1} , it is possible for an EHV [C I] outflow to drive the HV CO outflow with $T_R = 0.003$ K for GL 2591 0.04 K for W28 A2. If present, such low-intensity wing emission would be extremely difficult to detect using available instrumentation.

4.2. Jet Models

If sufficiently low limits to the EHV [C II] emission can be set and if the EHV wing traces the velocity field of the wind, our nondetection of EHV [C I] would call into question the standard analysis of mass-loss rate from the HV flow, assuming momentum conservation and a timescale given by the size of the flow and a characteristic velocity. These calculations have been challenged on other grounds (Parker, Padman, & Scott 1991), but they also have found some support in detections of H I wings at the predicted levels (Giovanardi et al. 1992) and in comparison of mass-loss rates from Na I with those deduced from the usual method (Natta & Giovanardi 1990).

If standard methods have overestimated the mass-loss rates, then jets are an alternative driving source for molecular outflows (Masson & Chernin 1993; Raga et al. 1993; Stahler 1994). Models using jets to drive outflows would be favored if the carbon in the wind cannot be detected in any form because the jets have mass-loss rates lower than those inferred from the standard analysis of wind-driven outflows (Masson & Chernin 1993). Thus, the jet itself would presumably be undetectable in CO or [C I]. However, Hartigan, Morse, & Raymond (1994) have found evidence that mass-loss rates in jets are higher than previously thought.

In the picture of jet-driven outflows, the EHV CO emission would probably arise from ambient gas which has been entrained by the jet. In the picture of wandering jets, this material would have been shocked by the jets. Models of chemistry in shocks (Neufeld & Dalgarno 1989) predict ratios of C^0 to CO less than what we inferred for a wind model by factors of ~ 100 . Therefore the [C I] intensity predicted by the shocked

gas model is a few times less than our detection limit. If shocks do not occur in the entrainment process, we can assume that the C^0 to CO ratio in the EHV gas is identical to the column density ratio in the HV gas (0.07 in the blue wing of GL 2591) observed by Walker et al. (1993). In this case, the $[C\ I]$ intensity prediction is less than our detection limit by a factor of ~ 30 for GL 2591.

5. SUMMARY

We have set limits on the emission of $[C\ I]$ in the EHV wings of GL 2591 and W28 A2. These limits are considerably below the predictions of a picture in which the EHV gas is the stellar wind which drives the HV molecular outflow. Taken at face

value, this result would support the idea that mass-loss rates have been overestimated by the standard analysis of the wind-driven model in these sources, allowing models using jets to drive the outflows to be viable. However, the wind-driven picture could still be viable if most of the carbon in the wind is in the form of C^+ or if most of the wind emission is at higher velocities, producing a weaker, wider line in either CO or $[C\ I]$.

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