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SULFUR ISOTOPES AND MOLECULAR OUTFLOWS ASSOCIATED WITH NEWLY FORMED MASSIVE STARS

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RESUMEN

En este trabajo se discuten dos resultados observacionales nuevos sobre el gas molecular asociado a regiones H II ultracompactas. El primero es el reciente descubrimiento hecho por Henkel et al. (1995) de que el cociente de abundancias de $^{32}S/^{34}S$, deducido de las observaciones de las especies isotópicas de CS está fuertemente correlacionado con la distancia galactocéntrica, mientras que $^{34}S/^{33}S$ no lo está. El segundo es el estudio estadístico de CO (J=1–0) a alta velocidad hacia una muestra de 94 regiones H II ultracompactas. El 90% de esta muestra tiene un exceso en el ala de la línea en emisión con velocidades >15 km s^{-1}. Varias de estas regiones han sido mapeadas y se encuentran flujos bipolares. La masa, energía cinética y tasa de transporte de momento en los flujos son un orden de magnitud mayores que los encontrados hacia estrellas de baja masa. Se postula que los flujos son producidos por estrellas masivas, aunque no necesariamente las estrellas ionizantes de las regiones H II.

ABSTRACT

This paper discusses two new observational results for the molecular gas associated with ultracompact (UC) H II regions. The first is the recent discovery by Henkel et al. (1995) that the $^{32}S/^{34}S$ abundance ratio, as inferred from observations of CS isotopes, is strongly correlated with galactocentric distance while $^{34}S/^{33}S$ is not. The second is a statistical study of high velocity CO (J=1–0) toward a sample of 94 UC H II regions. Fully 90% of this sample has excess line wing emission with velocities >15 km s^{-1}. Several of these have been mapped and found to be bipolar flows. The mass, kinetic energy, and rate of momentum transport in the flows are about an order of magnitude greater than found toward low mass stars. It is postulated that the flows are driven by massive stars, although not necessarily the ionizing stars of the observed UC H II regions.

Key words: **ISM: ABUNDANCES — ISM: OUTFLOWS — H II REGIONS**

1. SCOPE

This will not be a comprehensive review of the environments of newly formed massive stars both because this topic is too extensive to cover in the allotted time and several relatively recent reviews have been published (e.g., Churchwell 1990, 1991, 1993, 1994; Zylka 1994). Instead, I will concentrate on two, as yet unpublished, results found for the molecular gas associated with ultracompact (UC) H II regions which may have important consequences for our understanding of massive star formation and galactic nucleosynthesis processes. In particular, I will discuss recent measurements of sulfur isotopic abundance ratios toward UC H II regions as a function of galactocentric distance and molecular outflows associated with massive star formation regions.

2. SULFUR ISOTOPIC ABUNDANCES

Chin et al. (1995) measured the J=2–1 transition of $^{12}C^{32}S$, $^{12}C^{34}S$, $^{12}C^{33}S$, and $^{13}C^{32}S$ toward 20 southern hemisphere UC H II regions located at galactocentric distances 3–9 kpc. All sources had a main beam brightness temperature ≥ 0.85 K in the $^{12}C^{34}S$ line using the SEST telescope (HPBW $\approx$ 53"). Dual beam switching at a rate of 6 Hz and a throw of 11′ 40″ in Az was used.

$^{12}C^{32}S$ was optically thick in all sources. Consequently, the intensity ratio I($^{12}C^{32}S$)/I($^{12}C^{34}S$) was not equivalent to the $^{32}S/^{34}S$ isotopic abundance ratio. However,

$$\frac{^{32}S}{^{34}S} \approx \left(\frac{^{12}C}{^{13}C}\right) \frac{I(^{13}C^{32}S)}{I(^{12}C^{34}S)}. \tag{1}$$

if both $^{13}C^{32}S$ and $^{12}C^{34}S$ are optically thin, have the same excitation temperature, are spatially coincident, and chemical fractionation is unimportant. The $^{12}C/^{13}C$ abundance ratio has been extensively studied by Henkel, Wilson, & Bieging (1982) and Henkel, Güsten, & Gardner (1985) using isotopes of H_2CO and by Langer & Penzias (1990) using isotopes of $C^{18}O$. Using all available data, Wilson & Rood (1994) found the following gradient with galactocentric distance D_G for the $^{12}C/^{13}C$ abundance ratio:

$$\frac{^{12}C}{^{13}C} = (7.5 \pm 1.9)\frac{D_G}{\mathrm{kpc}} + (7.6 \pm 12.9). \tag{2}$$

The sulfur isotope abundance ratio

$$\frac{^{34}S}{^{33}S} \approx \frac{I(^{12}C^{34}S)}{I(^{12}C^{33}S)}, \tag{3}$$

if both species are optically thin, have the same excitation temperature, and do not suffer significant chemical fractionation or photon trapping.

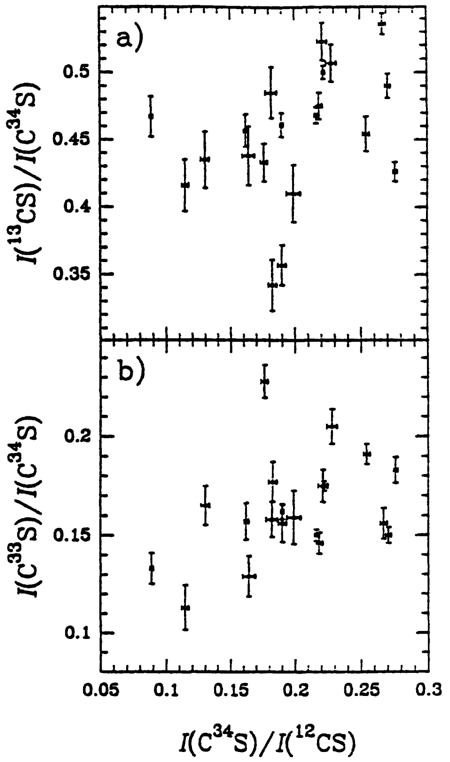
2.1. Line Saturation and Photon Trapping

The importance of line saturation and photon trapping (i.e., modification of excitation temperatures from the optically thin values due to line saturation) was investigated in two ways. One, statistical equilibrium calculations using an LVG code for a density of 10^5 cm^{-3} and a kinetic temperature of 30 K showed that only when the optical depths of $^{12}C^{32}S$ and $^{12}C^{34}S$ are ≥ 5 and ≥ 1, respectively, do the rotational excitation temperatures of $^{12}C^{34}S$, $^{13}C^{32}S$, and $^{12}C^{33}S$ differ from each other by more than about 20%. Since most of the sources in the Chin et al. sample had $\tau(^{12}C^{32}S) \sim 5$, these calculations imply that line saturation effects should be small. Five sources in their sample, however, had $\tau(^{12}C^{32}S) > 9$. Two, an empirical test of the importance of line saturation can be obtained from the intensity ratios of $^{13}C^{32}S/^{12}C^{34}S$ and $^{12}C^{33}S/^{12}C^{34}S$ versus $^{12}C^{34}S/^{12}C^{32}S$. In both cases, one would expect that as saturation increases in the two most abundant species ($^{12}C^{32}S$ and $^{12}C^{34}S$), the ratios $^{13}C^{32}S/^{12}C^{34}S$ and $^{12}C^{33}S/^{12}C^{34}S$ should increase as $^{12}C^{34}S/^{12}C^{32}S$ increases. In fact, no evidence of such a correlation was found in the data (see Figure 1).

2.2. Chemical Fractionation

It is well known that the $^{12}C/^{13}C$ isotopic ratio obtained from CO is chemically fractionated by the exchange reaction $^{13}C^+ + ^{12}CO \rightarrow ^{12}C^+ + ^{13}CO + \Delta E_{35K}$ which enhances ^{13}CO in cold diffuse C^+ regions of molecular clouds at the expense of ^{12}CO. A similar reaction $^{13}C^+ + ^{12}CS \rightarrow ^{12}C^+ + ^{13}CS + \Delta E_{25K}$, also holds for CS. However, this is expected to be less important in the case of CS because CS arises from the densest parts of molecular clouds where C^+ is much less abundant than in the more diffuse medium traced by CO. Molecules such as CH, H_2CO, HCN, and C_2H which form from C^+, but for which no isotopic exchange is believed to occur , should have a larger $^{12}C/^{13}C$ isotopic ratio than that of CO. CS should be fractionated intermediately between CO and H_2CO, so we should expect

$$\frac{^{12}CO}{^{13}CO} < \frac{^{12}CS}{^{13}CS} < \frac{H_2\,^{12}CO}{H_2\,^{13}CO}. \tag{4}$$



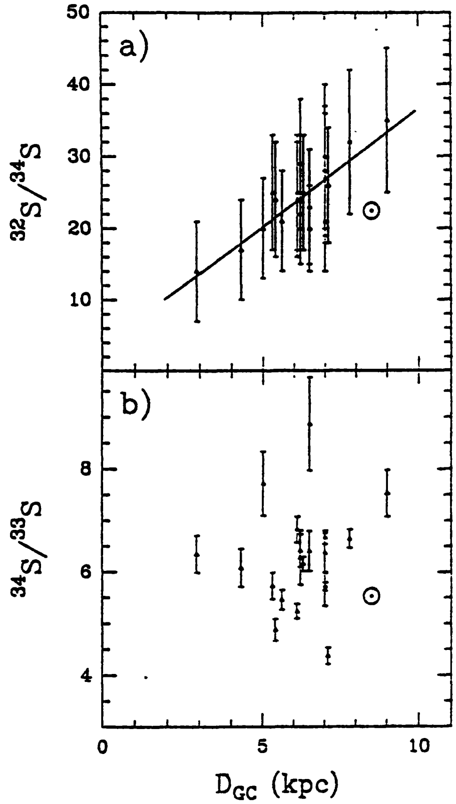


Fig. 1. (*Left*) Intensity ratios of CS isotopes vs. I($C^{34}S$)/I(^{12}CS). If $C^{34}S$ (J=2–1) were saturated, a positive correlation between the plotted intensity ratios would be expected.

Fig. 2. (*Right*) Sulfur isotopic abundance ratios as a function of galactocentric radius. The solar values are indicated by the sun symbol and the solid line is a least square fit to the data.

In fact, observations show that the $^{12}C/^{13}C$ isotopic ratio found from isotopes of H_2CO and CO are indistinguishable (Henkel et al. 1982; Langer & Penzias 1990). This leads us to conclude that, within observational accuracy,

$$\frac{^{12}\mathrm{CS}}{^{13}CS} \approx \frac{^{12}\mathrm{C}}{^{13}\mathrm{C}}. \tag{5}$$

We have no reason to believe that the sulfur isotopes will be chemically fractionated in the interstellar medium, but have no evidence to support this.

2.3. Results

The results of the Chin et al. (1995) study are illustrated in Figure 2. In the interval $3 < D_G < 9$ kpc, the average value of $^{32}S/^{34}S \approx 24.4 \pm 5.0$ and $^{34}S/^{33}S \approx 6.27 \pm 1.01$, the same as the solar values within the uncertainties. Most surprising, however, is the gradient of $^{32}S/^{34}S$ with D_G and the lack of any such correlation for $^{34}S/^{33}S$. The $^{32}S/^{34}S$ gradient was found to be:

$$\frac{^{32}\mathrm{S}}{^{34}\mathrm{S}} = (3.3 \pm 0.5)\frac{D_G}{\mathrm{kpc}} + (4.1 \pm 3.1), \tag{6}$$

with a correlation coefficient of 0.84. The slope is about half that of the $^{12}C/^{13}C$ gradient. These data imply that ^{34}S and ^{33}S vary together and, either ^{32}S increases with D_G and ^{34}S and ^{33}S are constant with D_G, or ^{32}S is approximately constant with D_G and ^{34}S and ^{33}S decrease with D_G.

2.4. Conclusions

The sulfur isotopes are formed only in massive stars via oxygen and silicon burning. Type Ia supernovae are thought to produce ~40% of ^{32}S (Thielemann, Namoto, & Ashimoto 1994) and the other supernovae (Types II, Ib, and Ic) produce together ~60%. Timmes, Woosley, & Weaver (1995) find that all supernovae excluding Type Ia, under produce ^{33}S and over-produce ^{34}S relative to ^{32}S. In Type Ia supernovae Thielemann et al. (1994) find the opposite to be true. Perhaps of most relevance to our observations is the fact that the final abundances of all supernovae appear to be independent of their initial metal abundances. This makes it difficult to understand a galactic sulfur isotopic gradient with D_G in terms of a galactic disk metal gradient. A strong ^{32}S/^{34}S gradient with D_G while no correlation is detected of ^{34}S/^{33}S with D_G is difficult to understand in terms of our present knowledge of thermonuclear processes in massive stars and the distribution of supernovae types in the galactic disk. This leads us to postulate one of three possible conclusions. One, either the CS isotopes suffer more than expected from chemical fractionation, or photon trapping, or transfer effects, or the application of the ^{12}C/^{13}C gradient is incorrect, or some combination of the above. Or, two, the ratio of Type Ia to other supernovae changes with D_G such that ^{32}S increases with D_G. However, it is not clear that this can also explain the behavior of ^{34}S/^{33}S with D_G. Or, three, our understanding of nucleosynthesis in and chemical evolution of massive stars may require modification. Prudence dictates that further observations and independent confirmation of the Chin et al. (1995) results should be obtained before pursuing possibilities two and three.

3. MOLECULAR OUTFLOWS TOWARD UC H II REGIONS

Until 1988, it was generally assumed that by the time massive stars formed detectable H II regions they had reached the main sequence and were not expected to drive outflows or evidence any activity associated with mass accretion. However, Harvey & Forveille (1988) discovered the most luminous outflow detected until that time apparently associated with the UC H II region G5.89. Several other outflows have since been detected toward massive star formation regions, including an extensive study of DR21 by Garden and coworkers (Garden et al. 1991a, b; Garden & Carlstrom 1992). The outflows toward these objects are much more luminous and massive than those detected toward low mass stars. These results raise a host of questions about the association of molecular outflows with massive star formation, such as: What is the mechanism that drives the outflows? Are the ionizing stars of UC H II regions the central engines of the molecular outflows? How common is the association of UC H II regions with molecular outflows? What role might stellar winds, rotation, magnetic fields, and accretion disks play in the outflow process? Are there any systematics in the outflow morphologies and energetics with age and luminosity of the star responsible for the outflow?

Shepherd & Churchwell (1995; hereafter SC) have begun a systematic study of high velocity molecular gas associated with a large number of UC H II regions to address some of the above questions. They observed CO (J=1–0) line profiles toward 94 UC H II regions with the NRAO 12m telescope (HPBW=60″; velocity resolution=2.6 km s^{-1}) to rms noise levels of $\sim$ 20 mK antenna temperature corrected to above the atmosphere. Of primary interest were sources with line wings in excess of that implied by a Gaussian fit to the line core (i.e., in excess of random thermal and turbulent motions). In Figure 3 the measured full width (FW) at 20 mK is plotted against the FW at 20 mK of a Gaussian fit to the line core. For FWs > 15 km s^{-1}, all sources show excess line wing emission and the excess increases as FW(Gaussian) increases. Fully 90% of the sample had excess line wing emission. The statistical results are given in Table 1.

SC emphasized that with a 60″ HPBW and line profiles only toward a single position, the origin of the high velocity gas is uncertain. Also the nature of the high velocity gas is unknown; it could be due to rotation, contraction, expansion, jets, bipolar outflows, or some combination of the above. If the excess line wing emission is due to bipolar outflows, then we would conclude that outflows are a common feature of early massive star evolution, but these data cannot be used to support this supposition.

The origin and nature of the motions implied by the observed line wings can only be ascertained by mapping the line wing emission. The line wings were mapped by SC toward two UC H II regions, G25.65 and G240.31. These are shown in Figures 4 and 5, respectively, and in Table 2 the derived properties of the outflows are given along with the position, kinematic distance, and spectral type of the ionizing star of the UC H II regions. R_{flow} is the projected separation of the red and blue shifted lobes, v_{ch} is the expansion rate of the flow, τ_d is the dynamical age of the outflows based on the flow velocities and separations, M is the mass in the indicated part of the flow, $\dot{P}$ is the rate of momentum carried away in the flows, E is the total kinetic energy in the flows, and L is the mechanical luminosity of the flows.

From Figures 4 and 5, we see that the UC H II regions (indicated by stars) are, within the errors, on the axes of the flows and reasonably centered between the red and blue shifted lobes. This would seem to imply that the flows originate from, and are driven by, the central star of the UC H II regions. Further, we see that the mass in the flows are enormous relative to that of the ionizing stars, but the mechanical luminosity of the flows

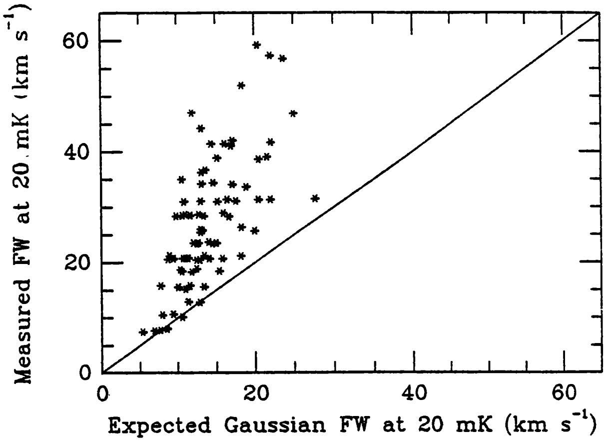
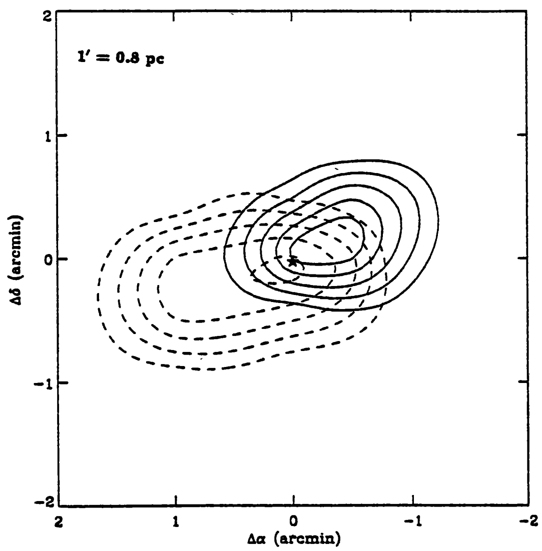


Fig. 3. The measured FW at 20 mK (*s) versus the FW at 20 mK of a Gaussian fit to the line core (solid line). For FW > 15 km s^{-1}, the measured FWs are exceed the expected values by increasing amounts.



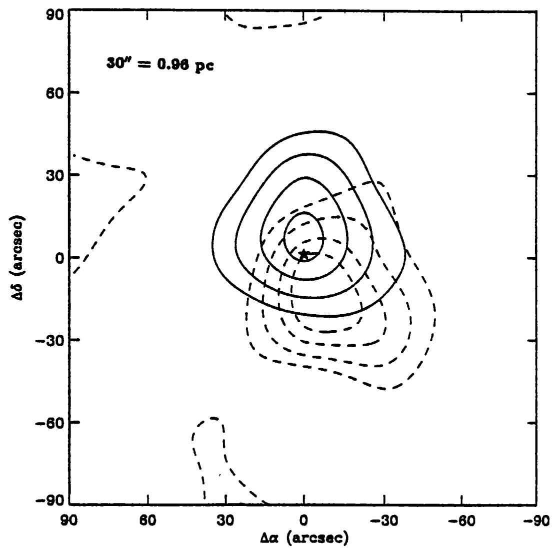


Fig. 4. (*Left*) The CO (1–0) outflow associated with G25.65+1.05. The blue lobe (dashed contours) is integrated from 25.8 to 31.1 km s^{-1}. The red lobe (solid contours) is integrated from 54.6 to 62.3 km s^{-1}. The position of the UC H II region is indicated by a star.

Fig. 5. (*Right*) The CO(1-0) outflow associated with G240.31-0.07. The blue lobe (dashed contours) is integrated from 45.4 to 53.5 km s^{-1}. The red lobe (solid contours) is integrated from 79.5 to 84.7 km s^{-1}. The UC H II region is indicated by a star.

TABLE 1

RESULTS

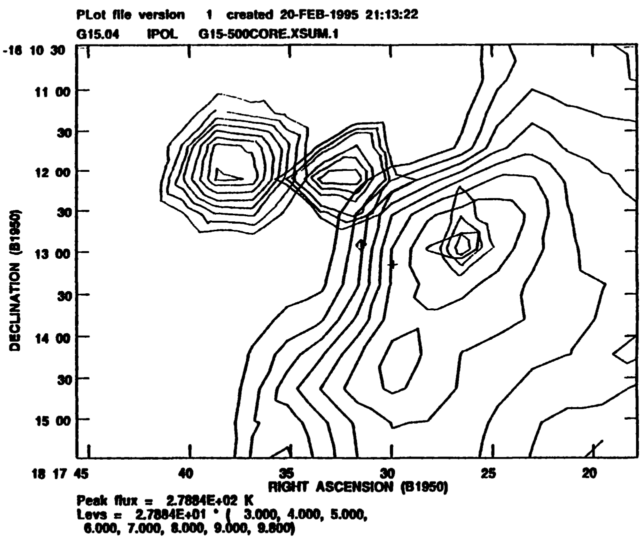
Profile Definition	FW(20 mK) ($km\ s^{-1}$)	% of Sample	Example
No excess line wings	< 15	9.5	G234.61
Moderate excess	$15 - 30$	49.5	G125.60
HV wings	$30 - 45$	29.5	G111.25
EHV wings	> 45	11.5	G173.58

TABLE 2

UC H II REGION AND MOLECULAR FLOW PROPERTIES

Property	G25.65+1.05	G240.31+0.07
$\alpha(1950)$	$18^h31^m40.1^s$	$07^h42^m45.1^s$
$\delta(1950)$	$06°02'06''$	$-24°00'24''$
Kinematic distance	2.75 kpc	6.6 kpc
Spectral Type	B1	B0.5
R_{flow}	0.53 pc	0.38 pc
v_{ch}	29.2 km s^{-1}	16.3 km s^{-1}
τ_d	1.8×10^4 yr	2.3×10^4 yr
M_{red}	24.1 $M_\odot$	55.3 $M_\odot$
M_{blue}	54.3 $M_\odot$	29.5 $M_\odot$
M_{total}	78.4 $M_\odot$	84.8 $M_\odot$
$\dot{P} = \sum(M_{flow}v)/\tau_d$	0.08 $M_\odot$ km s^{-1} yr^{-1}	0.04 $M_\odot$ km s^{-1} yr^{-1}
$E=\frac{1}{2}\sum(M_{flow}v^2)$	2.8×10^{47} erg	1.1×10^{47} erg
$L=\dot{E}/\tau_d$	128 $L_\odot$	40 $L_\odot$

are small relative to the radiative luminosity of the ionizing stars. The kinetic energies and rate of momentum transport in the molecular flows are very much larger than that in B-type stellar winds. In fact, the large values of M, E, and $\dot{P}$ in these flows probably indicate that the flows are driven by massive stars since they are at least an order of magnitude larger than those typically found for low mass stars. However, with a spatial resolution of only 60″, these data do not prove unambiguously that the flows are driven by the star that powers the UC H II region. We must realize that in the immediate vicinity of UC H II regions, an entire cluster of emerging stars are generally present (see Kurtz, Churchwell, & Wood 1994). Only the most massive stars are detectable at radio wavelengths via their ionizing radiation, and the youngest ones of these may not be detected if mass accretion rates are high enough to absorb ionizing radiation close to the star so that no UC H II can form. In fact, Shepherd (1995) has found two outflows where the UC H II region is either well off the flow axis or is very asymmetrically located relative to the positions of the red and blue shifted lobes. These are shown in Figures 6 and 7. Certainly, in the case of G15.04 the central star of the UC H II region cannot be responsible for the flow and we suspect that this is also probably true for the flow toward G192.16. Thus, the situation is not clear. Toward G25.65, G240.31, DR 21, and G5.89 there is every reason to believe that the flows are powered by the central stars of the H II regions since they are symmetrically situated on the flow axes; but, toward G15.04 and probably G192.16 the flows do not appear to have anything to do with the UC H II regions.



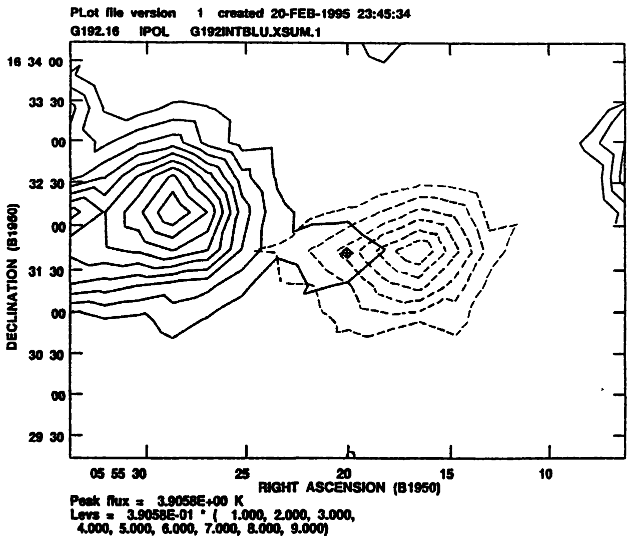


Fig. 6. (*Left*) The CO bipolar flow toward G15.04. The heavy solid contours indicate ambient CO gas. The UC H II region is indicated by ⊕, an H_2O maser is indicated by +, and the red and blue lobes of the outflow are labeled R and B. Note that the UC H II region is far from the flow axis.

Fig. 7. (*Right*) The CO bipolar flow toward G192.16. The red lobe has dashed contours and the blue one has solid contours. The UC H II region is indicated by ⊕. Note that the H II region is asymmetric relative to the two lobes.

If the flows are not driven by the central star of the UC H II regions, then what is the source of the flows? As we argued above, the large masses and energies associated with the flows strongly suggest that the central engine is probably a massive star. If it does not reside in the UC H II region and it is massive, why don't we see the an H II region associated with the star? We postulate that the driver of the flows is probably a massive protostar (at an earlier evolutionary stage than the star that powers the UC H II region) that has not been able to form a detectable H II region yet because of rapid mass accretion. Such an object might be detectable in the infrared due to a warm dust cocoon and/or a massive, spinning accretion disk. In addition to IR continuum emission, *high excitation* molecular transitions of molecules such as CH_3CN, NH_3, and CS might be good probes of the warm, dense gas accumulated around the protostar.

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