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CO $J=3\rightarrow2$ and Submillimetre Continuum Observations of Two Molecular Outflow Sources

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Received February 5, accepted August 20, 1982

Summary. We present CO $J=3\rightarrow2$ molecular line spectra, and submillimetre photometry at wavelengths $\lambda\lambda 377\mu m$, $811\mu m$, and $1136\mu m$ for the sources L1551 and IRC+10.216. Detailed analysis of the L1551 spectra indicates the presence of strong velocity gradients in the CO emission zones, implying low optical depths and relatively high densities. The central source IRS 5 displays an infrared excess which cannot be explained in terms of a single temperature continuum. The emission zone is probably compact with respect to the instrumental beam size at the wavelength of peak emission ($\lambda \sim 50\mu m$), and may represent an accretion disc responsible for collimation of the high velocity gas. The far-infrared continuum of IRC+10.216 has been synthesised by assuming a distribution of optically thin grains whose emissivity varies as $\nu \propto \lambda^{-1}$, and the CO $J=3\rightarrow2$ spectrum for this source supports earlier $J=2\rightarrow1$ observations, implying a variable mass-loss rate.

Keywords: CO $J=3\rightarrow2$ - submillimetre photometry - stellar outflows

Table 1. Submillimetre continuum photometry

<table>
<thead>
<tr>
<th>Source</th>
<th>Effective wavelength (µm)</th>
<th>Bandpass (GHz)</th>
<th>Flux (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1551</td>
<td>377</td>
<td>420</td>
<td>107 ± 8</td>
</tr>
<tr>
<td>L1551</td>
<td>811</td>
<td>140</td>
<td>15.0 ± 3.0</td>
</tr>
<tr>
<td>IRC+10.216</td>
<td>377</td>
<td>420</td>
<td>35.2 ± 6.6</td>
</tr>
<tr>
<td>IRC+10.216</td>
<td>811</td>
<td>140</td>
<td>9.8 ± 1.6</td>
</tr>
<tr>
<td>IRC+10.216</td>
<td>1136</td>
<td>85</td>
<td>3.5 ± 0.9</td>
</tr>
</tbody>
</table>

2. The Observations

The CO $J=3\rightarrow2$ (345 GHz) spectra were obtained with the QMC submillimetre and millimetre spectral line receivers during December 1980. The instrumental beamwidth was 10º, system noise temperature measured to be 420 K, and zenith optical depth was typically of order ~0.3. The spectra were calibrated in the usual way (White et al., 1979) to yield corrected antenna temperature $T_a^*$, and are estimated to be accurate to better than 15%. Absolute telescope pointing capability was measured using SAO stars and found to have an RMS value of order ~15º.

The continuum data (Table 1) were obtained with the QMC submillimetre photometer which has been described previously (Robson et al., 1978). For these observations three passbands were employed with mean frequencies 264 GHz (1136 µm), 370 GHz (811 µm), and 796 GHz (377 µm) with bandwidths of 85 GHz, 140 GHz, and 420 GHz, respectively. The detector was a $^3$He cooled composite Ge bolometer with an electrical NEP of $3 \times 10^{-13}$ W Hz$^{-1/2}$. Calibration is primarily by comparison with the planet Mars for which we assume that the submillimetre emission is adequately described by the model of Wright (1976). For these observations a secondary calibration via Jupiter was used. The measured brightness temperature for Jupiter with respect to Mars through these passbands is given in Cunningham et al. (1981). The HPBW for all three channels was measured to be 86º. Offset guiding on SAO stars was used to define source positions.

3. L1551

The dark cloud L1551 is a nearby region of star formation characterised by substantial kinematic activity. Within its bound-

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Snell et al. (1980) hypothesize that the bipolar CO complex originates from the interaction of high velocity jets from IRS 5 with a circumstellar cloud. Their results further indicate that CO wing emission may be optically thin at several locations in this region.

In order to specify the properties of this CO cloud more clearly, we have taken \( J=3\rightarrow 2 \) CO profiles at three locations in L 1551. Two of these spectra (one of which indicates optically thick emission) have been briefly discussed by White et al. (1981). We have also observed the optically thin zone near \( \lambda(1950)=04^h28^m31^s, \delta(1950)=17^\circ 59'52'' \), and our results are presented in Fig. 1.

In discussing their \( J=1\rightarrow 0 \) results, Snell et al. (1980) were able to determine that kinetic temperatures in the line wing range between 8 K and 35 K. Our present results supplement this data (the beam-size for the present work is essentially the same as that of the lower frequency results), and enable tighter constraints on the physical conditions responsible for this emission.

Where local gas kinetic temperature \( T \) and the \( \text{H}_2 \) density \( n_{\text{H}_2} \) lead to thermalisation of the lower rotational energy states of CO, the observed antenna temperature will be given by

\[
T_a^* (J+1\rightarrow J) = 5.53(J+1) \left[ \frac{1}{e^{\frac{T}{T}}} - 1 \right] - \frac{1}{1 - e^{\frac{T_m}{T}}} - 1
\]

\[
(1 - e^{-12.6J(J+1)}) W,
\]

where

\[
\tau_{J+1\rightarrow J} = \tau_{J+0\rightarrow J+1} e^{\frac{2.76J(J+1)}{T}} \left( \frac{1 - e^{-5.53J(J+1)/T}}{1 - e^{-5.53/T}} \right).
\]

\( W \) is dilution, \( \tau \) is the optical depth, and \( J \) is the total angular momentum quantum number of the lower transition state.

The use of all three CO profiles in Fig. 1 in conjunction with Eq. (1) enables a least-squares solution to be calculated for \( W, T \) and \( \tau_{J+0} \). Results of this analysis for the wing feature are presented in Fig. 1. By further assuming a \( [^{12}\text{CO}]/[^{13}\text{CO}] \) ratio of \( \sim 40 \) and employing the values \( T, W, \) and \( \tau_{J+0} \) found above, it is possible to determine a \( ^{13}\text{CO} \) \( J=1\rightarrow 0 \) profile which compares very favourably with observations (Snell et al., 1980).

Several interesting results ensue from such an analysis. First, the kinetic temperatures obtained are moderately high \( T \sim 25\rightarrow 30 \) K, and appear more or less constant over the velocity regime for which this parameter can be reliably evaluated. Similarly, the dilution \( W \) appears broadly invariant, having typical values \( W \sim 0.3 \); a result which was not available to Snell et al. with their more limited data base. Finally, the CO line shape is seen to arise primarily from changes of optical depth; although \( \tau_{J+0} < 1 \), in the higher frequency transitions optical depth \( \tau_{J+1\rightarrow J} > (J+1) \) is significantly greater than unity — a factor responsible for the comparability of \( J=3\rightarrow 2 \) and \( J=2\rightarrow 1 \) line wing strengths.

Using the parameters discussed above, and assuming a uniform velocity gradient through the wing emission region, we may therefore determine a CO column density

\[
N(\text{CO}) = \frac{2.85 \times 10^{14} \tau_{J-0} dV (\text{km s}^{-1}) T}{(1 - e^{-5.53/T})} \sim 2.8 \times 10^{16} \text{ cm}^{-2}
\]

or, taking \( |\text{CO}|/|\text{H}_2| \sim 5 \times 10^{-5} \), this gives \( N(\text{H}_2) \sim 5.5 \times 10^{20} \). Adopting a local \( \text{H}_2 \) density \( n(\text{H}_2) \sim 10^{4} \text{ cm}^{-3} \) (required for the
assumed level of CO thermalisation) implies a wing column depth $\Delta r \lesssim 0.081 \text{ pc}$; considerably less than the overall size of the emission region ($\sim 0.3 \text{ pc}$). Such a result strongly suggests that the wing emission arises from warm, dense post-shock material, with low dilution $W$ indicating substantial fragmentation in the post shock zone.

The spike component in contrast shows a strongly attenuated $J = 3 \rightarrow 2$ line strength compared with lower frequency results, and it is instructive to briefly discuss possible causes for this behaviour.

If CO rotational levels are thermalised, the observed temperature ratio

$$\chi = T_{\text{ex}}(J = 3 \rightarrow 2)/T_{\text{ex}}(J = 1 \rightarrow 0) \sim 0.42$$

is obtained for $T \approx 6.6 \text{ K}$. Since, however, this implies (for $W \sim 1$) a value $T_{\text{ex}}(J = 1 \rightarrow 0) \sim 3.4 \text{ K}$ which is considerably less than observed, this explanation does not appear to be viable. Alternatively, a low ratio $\chi$ may originate if $\tau_{2 \rightarrow 1}/\tau_{1 \rightarrow 0} < 1$. Again, however, this can be shown to imply $T \lesssim 6.2 \text{ K}$ and unrealistically low line strengths.

It seems therefore clear that the observed range of spike temperatures reflects the influence of photon-trapping effects. Adopting from the observed $J = 1 \rightarrow 0$ line strength a provisional gas kinetic temperature $T \sim 14.3 \text{ K}$, we have employed an LVG analysis similar to that of Goldreich and Kwan (1974), using the CO collisional rates of Green and Thaddeus (1974) to obtain the contour map in Fig. 2. It is plain from this that an adequate fit to all three transition temperatures may be obtained. In particular, the analysis permits us to define unique values of $n_{\text{H}_2} \sim 6.8 \times 10^3 \text{ cm}^{-3}$ and $dV/dr \sim 56 \text{ km s}^{-1} \text{ pc}^{-2}$, with an uncertainty of $\pm 0.1 \text{ dex}$ in each value. Contour maps at higher values of gas temperature $T$ have also been evaluated; we find that the values of $n_{\text{H}_2}$, $dV/dr$ thus determined are relatively insensitive to $T$, and for $T \lesssim 25 \text{ K}$ (the highest temperature case analysed) are the same within errors as the values quoted for $T \approx 14.3 \text{ K}$. Therefore, although it is not possible to claim a significant temperature differential between spike and wing features, the present analysis would appear to imply that the spike derives from a zone with strong velocity gradients. From the observed spike full width at half maximum $AV \sim 1.5 \text{ km s}^{-1}$ (obtained after deconvolution for instrumental frequency response), it is then possible to identify the spike as originating in a region of depth $\lesssim 2.7 \times 10^{-2} \text{ pc}$. Column density $N(\text{H}_2) \sim 5.6 \times 10^{20} \text{ cm}^{-2}$ is comparable to that of the wing, and implies optical extinction $A_V \sim 0.5 \text{ mag}$.

In achieving these results we have assumed that the $J = 1 \rightarrow 0$, $J = 2 \rightarrow 1$, and $J = 3 \rightarrow 2$ lines peak at the same velocity. If alternatively the $J = 2 \rightarrow 1$ line is considered displaced in frequency, as shown in Fig. 1, it is not possible to synthesise LVG line strengths consistent with observations. It may also be noted that very similar observations are obtained for optically thick wing zones (White et al., 1981) in L 1551, and the analysis of the spike feature considered here is therefore also pertinent to these cases.

As a result of this analysis it seems probable that the wing component in L 1551 is a post-shock phenomenon, with the relatively high temperatures representing some remnant of post-shock heating. The apparent presence however of large velocity gradients in the spike is rather surprising, since the spike feature appears to retain a more or less constant $V_{\text{LSR}}$ over the entire dark cloud region, and is an obvious candidate for emission from the pre-shock zone. This may in turn imply that the current analysis is quite inadequate, and other contributions (from say turbulence) should be considered. Alternatively, one might suppose that the spike emission derives from a region which has undergone a previous compressive phase, perhaps originating from radiative acceleration of placental material into the more widespread cloud region. Further observations are required however before it will be possible to discriminate between these and other options.

We have further investigated the far-infrared continuum of IRS 5 and our results, together with those of Fridlund et al. (1980),
Kwan, 1976), and this would imply a relatively small source size at \( \lambda \sim 50 \mu m \) (~2\prime), increasing rapidly however to longer wavelengths where \( x \gtrsim 1 \). It is possible in consequence that the present results seriously underestimate \( F_\nu \) at the longest wavelengths considered here, even allowing for present beam sizes.

Finally, we note that whilst no long-wave evidence is available for the size of IRS 5, the short wavelength emission clearly emanates from a warm, highly compact zone which may in turn be identifiable with the accretion disk hypothesized by Snell et al. (1980).

4. IRC+10 216

IRC+10 216 is a late type variable with moderate velocity gas outflow. The near-infrared spectrum appears to be composite, with evidence for optically thin SiC grain emission at wavelengths \( \lambda \sim 10 \mu m \) (cf. Treffers and Cohen, 1974).

The shorter wavelength (\( \lambda \lesssim 5 \mu m \)) continuum mimics a \( \sim 650 K \) black-body curve (cf. Becklin et al., 1969) but shows evidence for being highly polarised (Shaw and Sellner, 1970; Dyck et al., 1971; Capps and Knacke, 1976), and has been argued in consequence to represent scattering of the central star continuum (cf. Fazio et al., 1980).

Where source structure has been measured at wavelengths \( \lambda \lesssim 11 \mu m \), it appears to consist of two components: a small high temperature core, and a very much broader enveloping or "halo" zone. At \( \lambda = 11 \mu m \) this core is of size \(< 0.2 \prime\), and is thought to represent the central star (Sutton et al., 1979); an 1800 K blackbody representing this component has been indicated in Fig. 5.

Far-infrared photometry of this source at \( \lambda = 377 \mu m \), 811 \mu m, and 1136 \mu m is presented in Fig. 4, together with previously published infrared data. Apart from a discrepancy at \( \lambda \sim 350 \mu m \) between the present results and those of Campbell et al. (1976) (largely attributable to differing beam sizes), the present data is consistent with previous trends, and indicates a continuum falling as \( F_\nu \propto \nu^{-2} \). We have attempted to model this behaviour in terms of an optically thin grain distribution, and in accordance with the prescription of Fazio et al. (1980). This latter model assumes envelope density to fall with radius as:

\[
\rho(r) \propto \left(1 + \frac{r}{25}\right)^{-3/2}
\]

where \( \xi \) is grain opacity (\( \tau_0 \) is a constant), \( W \) is again dilution, and \( B_\nu(T) \) the Planck function corresponding to temperature \( T \). Two extreme cases are illustrated in Fig. 3; for Curve 1, \( x \) is assumed to be small, and/or \( \tau_0 \) large, with temperature taken as 95 K, i.e. the emission curve is that of a blackbody. For Curve 2, \( \tau_0 \) is assumed to be small, \( x \) is unity, and \( T = 40 K \), giving a variation \( F_\nu \propto B_\nu(T) \). The continuum observed longwards of 10 \mu m is seen to straddle these two extremes, and we find generally that no single temperature function of this kind can fully represent the data in this wavelength range, still less the short and long wavelength results combined.

It seems likely therefore that we must resort to models which take full account of radiative transfer effects and temperature variation through the cloud, in the manner of Scoville and Kwan (1976) and Tokunaga et al. (1978). For such cases, optical depth at the wavelength of peak emission is of order unity (Scoville and

Beichman and Harris (1981), and Strom et al. (1976), are presented in Fig. 3. Measurements were also taken at the location of optically thin CO results discussed earlier, resulting in a 2\sigma upper limit of 21.6 Jy at \( \lambda = 377 \mu m \). This suggests that the central source measures in Fig. 3 are contaminated very little by emission from the dark cloud region.

Corresponding least-squares fits to the continuum have been attempted using the function:

\[
F_\nu = W B_\nu(T)(1 - e^{-\tau_0})
\]

\[\tau_\nu = \tau_0 \nu^\alpha,\]

where \( \tau_\nu \) is grain opacity (\( \tau_0 \) is a constant), \( W \) is again dilution, and \( B_\nu(T) \) the Planck function corresponding to temperature \( T \). Two extreme cases are illustrated in Fig. 3; for Curve 1, \( x \) is assumed to be small, and/or \( \tau_0 \) large, with temperature taken as 95 K, i.e. the emission curve is that of a blackbody. For Curve 2, \( \tau_0 \) is assumed to be small, \( x \) is unity, and \( T = 40 K \), giving a variation \( F_\nu \propto B_\nu(T) \). The continuum observed longwards of 10 \mu m is seen to straddle these two extremes, and we find generally that no single temperature function of this kind can fully represent the data in this wavelength range, still less the short and long wavelength results combined.

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\[
\rho(r) \propto \left(1 + \frac{r}{25}\right)^{-3/2}
\]

a function principally determined from \( J = 2 \rightarrow 1 \) CO mapping (Wannier et al., 1979). In addition however we assume a constant beam size \( B = 86'' \) (within \( \sim 15 \% \) of all but one of the beams used in the acquisition of the submillimetre data in Fig. 4), and a grain temperature:

\[
T_\nu = T_0 \left(\frac{r}{1''}\right)^{-\omega}
\]

appropriate for an \( r^{-2} \) grain heating function, where \( \omega = 2/(4 + \xi) \), \( \xi \) is defined through the grain emissivity law \( e \propto \lambda^{-\xi} \); and \( T_0 \) is a variable fitting parameter.

The best least-squares curve was obtained for \( T_0 \sim 230 K \), \( \xi = 1 \), and the fit is seen to be excellent, providing a strong indication that overall envelope properties are well represented by such a model. The internal radius was taken to be \( r \sim 0.074 \) corresponding to a maximum temperature \( T = 650 K \) and it is clear from the modelling that the near-infrared continuum may also be readily synthesized. The level of the direct contribution of this
emission to the observed continuum at these short wavelengths is difficult to gauge precisely because of the variable nature of the central star, a problem which also besets attempts to determine the integrated continuum energy (see later). Whilst these problems will ultimately require co-temporal near- and far-infrared measures before they can be properly overcome, it is possible to determine that at least a substantial fraction of near infrared flux may originate from the internal dust shell, rather than the central star. This radiation is then scattered by dust at larger radii to produce both the high levels of polarisation, and enhanced source radius (see later).

In adopting $\xi = 1$ we follow the lead of Campbell et al., although their revised data (Fazio et al., 1980) would suggest a value $\xi \approx 0.7$ to be more appropriate. In both cases $\xi$ is assessed from the slope of the observed continuum, a procedure which is strictly applicable only where the emission region has uniform temperature, and is entirely optically thin.

A potentially more sensitive way of evaluating $\xi$ is to determine the trend of source FWHM ($\sigma$) with wavelength. For centrally heated envelopes in which grain density decreases with increasing radius, $\sigma$ may be shown to vary as $\sigma \propto \lambda^{1/2}$, a result which is relatively insensitive to the precise details of envelope structure (Phillips and Beckman, 1980). Unfortunately, data concerning the size of IRC +10 216 shows significant omissions at longer wavelengths, and our own attempts to fill this gap (at $\lambda \approx 35 \mu m$) were compromised by short-wavelength filter leaks. Scan profiles at $\lambda = 20 \mu m$ with a $6^\circ$ beam indicated very little broadening over and above that expected for a point source, a result which is at least not inconsistent with the model, which predicts a source size $\sigma \approx 3.8$ and a FWHM after convolution with the beam of just $7.1^\circ$. Despite these deficiencies, the available long-wave data appears to imply a value $\xi \approx 1$ (Fig. 5), and in this respect provides further support for the underlying assumptions of our model. In the short wavelength ($\lambda \approx 5 \mu m$) scattering regime, $\sigma$ in contrast appears to asymptotically approach a value slightly in excess of $3.3^\circ$.

A further examination of envelope structure is possible through $J=3\rightarrow 2$ CO line profiles, and our results are presented in Fig. 6. Previous measures by Kuiper et al. (1976) in the $J=1\rightarrow 0$ CO transition showed a parabolic line profile indicative of constant velocity mass outflow, and these results were well modelled in terms of a constant temperature envelope. Subsequent $J=2\rightarrow 1$ mapping (Wannier et al., 1979) showed, however, a broad and roughly Gaussian variation of $T^*$ on the sky -- and indicated a size at variance with that expected for the constant mass-loss rate model of Kwan and Hill (1977). This result has been interpreted as indicating a secular decrease in $dM/dt$, and is the principal "raison d'etre" of Eq. (3). On the basis of this analysis, we have assumed $T^*_v$ to vary as

$$T^*_v(J=2\rightarrow 1) = T_{\text{max}}(J=2\rightarrow 1) e^{-4 \ln 2 (\sigma/\theta)^2}$$  \hspace{1cm} (5)

in modelling the $J=3\rightarrow 2$ spectrum, which thereby takes the form of a further test of the $T^*_v(J=2\rightarrow 1)$ mapping. The FWHM of this source is given by $\theta \approx 37^\circ$, and a value $T_{\text{max}}(J=2\rightarrow 1) = 30$ K is adopted. For these circumstances the variation of $T^*_v(J=3\rightarrow 2)$ with radial velocity $V$ is given (for constant outflow velocity) by Kuiper et al. (1976):

$$T^*_v(J=3\rightarrow 2, V) = T_{\text{max}}(J=3\rightarrow 2)(1 + (B/\theta)^2(1 - (V/V_0)^2)^{-1})^{-1}$$ \hspace{1cm} (6)

for optically thick lines. The parameter $V_0$ is a constant, and corresponds to the maximum observed radial velocity. This function is compared to our observed line profile in Fig. 6, and is
seen to give a reasonably good fit considering the noise. The present results therefore largely confirm lower frequency measures, and give some confidence that the source structure in CO is tolerably well established.

Finally, the far-infrared results may be combined with near infrared data (Fig. 4) to obtain a total continuum flux (with a proviso noted earlier concerning the variable nature of the central star). Temporarily placing aside the "excess" measurements at λ100μm and 20μm, we find total thermal emission + scattering to represent just 85% of the 1800K central star flux. A proportion of the residual energy will also be radiated as "excess" emission in the near-infrared, through SiC bending modes. The correspondence between these two energy integrals is therefore as good as may be expected considering the uncertainties, and suggests that the 1800K continuum in Fig. 4 is unlikely to deviate severely from the actual central star flux.

5. Conclusions

We have observed two stellar sources associated with high mass-loss rate outflows, at millimetre and submillimetre wavelengths.

References
