DETECTION OF CO\textsuperscript{+} WITH ISO TOWARDS THE PROTOSTAR IRAS16293–2422

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ABSTRACT

We observed the low luminosity (and low mass) protostar IRAS16293–2422 with the Long Wavelength Spectrometer on board the Infrared Space Observatory. The observed line spectrum is very rich and shows transitions of several molecules and atoms. Here we report the detection of eight high-N rotational transitions of CO\textsuperscript{+}. This is the first time that CO\textsuperscript{+} has been detected in a low luminosity source and the first time that high-N lines have been detected in any source. The detection of these lines was not predicted by models and consequently, their interpretation is a challenge. We discuss the possibility that the observed CO\textsuperscript{+} emission originates in the dense inner regions illuminated by the UV field created in the accretion shock (formed by infalling material), and conclude that this is an improbable explanation. We have also considered the possibility that a strong, dissociative J-shock at \sim 500 AU from the star is the origin of the CO\textsuperscript{+} emission. This model predicts CO\textsuperscript{+} column densities in rough agreement with the observations if the magnetic field is \sim 1 mG and the shock velocity is 100 km s\textsuperscript{-1}.

30 L\odot. Low-J CO transitions trace the presence of an outflow emanating from one component of the protobinary system, 1629A, and possibly another outflow originating in the second component, 1629B (Walker et al. 1993). Previous observations with the Kuiper Airborne Observatory (KAO) showed OI(63\mu m) line emission associated with the outflow which reveal the presence of a strong shock resulting from the interaction of the stellar wind with the surrounding medium (Cecarelli et al. 1997a). We observed IRAS 16293–2422 with the Long Wavelength Spectrometer (LWS) on board the Infrared Space Observatory (ISO) and detected several lines in the 45\mu m to 198\mu m range, in addition to the CO\textsuperscript{+} lines reported here (Cecarelli et al. 1997b, hereinafter Paper I); the CO rotational transitions from J\textsubscript{u}=14 to J\textsubscript{u}=25, several H\textsubscript{2}O and OH rotational lines, as well as the OI(63\mu m) and CI(157\mu m) fine structure lines. The high-J CO lines were interpreted as originating in a low velocity, non-dissociative C-shock (Draine, 1980) at about 15'' (=2500 AU) from the central object, where the wind obliquely strikes the outflow cavity walls; the H\textsubscript{2}O and OH lines probably originate in the same region. On the contrary, the CI(157\mu m) line comes from the UV-illuminated gas at the skin of the cloud to which IRAS 16293–2422 belongs.

Key words: sjiets and outflows – ISM: individual: IRAS 16293–2422 – Stars: formation – Infrared: ISM: lines

1. INTRODUCTION

IRAS 16293–2422 is a protobinary system, located at a distance of 160 pc in an isolated and cold molecular cloud core within the ρ Ophiuchus complex (Wootten 1989). This is one of the few sources in which infall has been claimed to occur simultaneously with outflow (Zhou 1995). Its bolometric luminosity is only

\textsuperscript{*}Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) with the participation of ISAS and NASA.

The CO\textsuperscript{+} molecule has a 2Σ ground electronic state in which each rotational level is split into two fine-structure levels: it has a fairly large dipole moment (μ = 2.771 D; Rosmus & Werner 1982), some 30 times larger than that of CO. Since the rotational constants of the two molecules differ by only 3%, CO and CO\textsuperscript{+} rotational transitions are at similar wavelengths, although the CO\textsuperscript{+} spontaneous emission coefficients are hundreds times greater than those of CO. However, the expected abundance of CO\textsuperscript{+} in interstellar clouds is 10 orders of magnitude lower than CO, so that to be detected, unexpectedly large amounts of CO\textsuperscript{+} have to be present. We present here the detection of eight CO\textsuperscript{+} lines, namely the rotational transitions from N=14→13 to N=21→20, towards IRAS 16293–2422.
Table 1. Parameters of the observed CO$^+$ lines. The statistical error is $0.2 \cdot 10^{-15}$ erg s$^{-1}$ cm$^{-2}$. $E_{up}$ is the energy of the upper level.

<table>
<thead>
<tr>
<th>$\lambda_{co}$ (µm)</th>
<th>$\lambda_{obs}$ (µm)</th>
<th>Flux (10$^{-15}$ erg s$^{-1}$ cm$^{-2}$)</th>
<th>Transition</th>
<th>$E_{up}$ (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>181.77</td>
<td>181.91</td>
<td>0.7</td>
<td>14-13</td>
<td>412</td>
</tr>
<tr>
<td>169.67</td>
<td>169.66</td>
<td>1.9</td>
<td>15-14</td>
<td>471</td>
</tr>
<tr>
<td>159.10</td>
<td>159.10</td>
<td>1.2</td>
<td>16-15</td>
<td>534</td>
</tr>
<tr>
<td>149.76</td>
<td>149.66</td>
<td>1.2</td>
<td>17-16</td>
<td>601</td>
</tr>
<tr>
<td>141.48</td>
<td>141.58</td>
<td>0.8</td>
<td>18-17</td>
<td>672</td>
</tr>
<tr>
<td>134.06</td>
<td>134.01</td>
<td>0.7</td>
<td>19-18</td>
<td>746</td>
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<tr>
<td>127.39</td>
<td>127.45</td>
<td>0.6</td>
<td>20-19</td>
<td>825</td>
</tr>
<tr>
<td>121.36</td>
<td>121.27</td>
<td>0.7</td>
<td>21-20</td>
<td>907</td>
</tr>
</tbody>
</table>

2. OBSERVATIONS AND RESULTS

IRAS 16293$-$2422 was observed during Revolution 85 (10 February 1996) with the LWS (Clegg et al. 1998). Spectra covering the 45µm to 198µm range were obtained with a spectral resolution $\sim$ 200 and calibrated against Uranus. The beam size was approximately 80" (Swinyard et al. 1996). Further details of the observations are reported in Paper I. We have reduced again these data using the Off-Line-Package (OLP) version 7, which improved the quality of the line spectra with respect to the previous analysis reported in Paper I.

The spectrum is dominated by the continuum emission, which is about 50 times brighter than the observed lines. The line spectrum is very rich, as mentioned in the Introduction. In some wavelength intervals, the spectrum is so rich that many lines are merged together or just barely separated making the definition of the baseline a very difficult task. As an example we show in Fig.1 an interval of 10µm, where we have so far identified eight of eleven lines present. Considering that at those wavelengths the spectral resolution is 0.6µm, the example shows well the difficulty of defining a clear baseline around each line.

![Figure 1. The line spectrum, after continuum removal (see Paper I for details) over a 10µm interval: in this small interval, eleven lines are detected, many of which overlap or are merged.](image1)

Bearing in mind the difficulties in determining reliable baselines, we estimate that the quoted fluxes for the CO$^+$ lines are uncertain by a factor of two. Although it is difficult to accurately derive their flux, the identification of these lines is clear, particularly given that we have detected the eight transitions with the lowest upper level energy in the LWS range. Fig.2 shows the CO$^+$ lines we identified in the spectrum: they cover all the eight rotational transitions from $N_u=14$ to $N_u=21$. Table 1 reports the parameters of the observed lines.

![Figure 2. Observed CO$^+$ lines including transitions from $N=14\rightarrow13$ (upper left) to $N=21\rightarrow20$ (lower right). Fluxes are in erg s$^{-1}$ cm$^{-2}$ and wavelengths are in µm. The solid curves show the gaussian best fits obtained assuming a linewidth equal to the spectral resolution element, 0.6µm. Identified lines in the range of each plot are also marked.](image2)

3. DISCUSSION

In Fig.2 we show the observed flux spectrum of the various CO$^+$ transitions. In the same figure the theoretical fluxes are shown for a slab obtained assuming that the levels are populated according to LTE conditions, and that the lines are optically thin. Although the optically thin assumption is probably correct, the LTE approximation will break down if the density is not sufficiently high to thermalise the levels. Therefore, the LTE curves in Fig.3 provide a lower limit to the gas kinetic temperature, and for each temperature, a lower limit to the CO$^+$ column density. In practice the lower limit to the gas temperature is set by the line ratios while the absolute flux constrains the column density. We find a minimum gas temperature of $T_{gas} \geq 300$ K is needed to match the line...
ratios. The estimated lower limit to the column density \( N(\text{CO}^+) \) depends on the unknown filling factor: the lower limit on \( N(\text{CO}^+) \) obtained by assuming a filling factor of unity and \( T_{\text{gas}}=1000 \text{ K} \) is \( \sim 7 \times 10^{10} \text{ cm}^{-2} \). This value scales almost linearly with \( T_{\text{gas}} \). However, since the \( \text{CO}^+ \) emitting gas is unlikely to fill the 80'' LWS beam and since the lower limit to the column density scales inversely as the presumed source size squared, \( N(\text{CO}^+) \) is likely to be substantially higher than this value. Integrating the line fluxes to find the total luminosity of the \( \text{CO}^+ \) lines and comparing with the similar lines of \( \text{CO} \) reported in Paper I shows that the \( \text{CO} \) lines are only five times more luminous than \( \text{CO}^+ \) lines. No existing model has ever predicted such a large luminosity for this molecular ion.

In cold molecular clouds the \( \text{CO}^+ \) abundance is predicted to be very low \( (\sim 10^{-12}) \) as it is efficiently destroyed by reactions with \( \text{H}_2 \), and formed at low rates via the ionisation of \( \text{CO} \) by cosmic rays. Standard chemistry (see for example the UMIST database, Millar et al. 1997) predicts a substantial \( \text{CO}^+ \) abundance enhancement only in regions where \( \text{CO}^+ \) formation occurs via the reaction of \( \text{C}^+ \) with \( \text{OH} \) (or \( \text{O}_2 \)), namely in regions where the \( \text{C}^+ \) ion and \( \text{OH} \) (or \( \text{O}_2 \)) molecule are simultaneously present. These conditions are found in dense \( \text{C}^+ / \text{CO} \) transition regions, where a far-UV field photodissociates the \( \text{CO} \) molecules and photoionises the atomic carbon, but at the same time is sufficiently shielded by the dense medium to allow the formation of \( \text{OH} \). The production of \( \text{OH} \) proceeds via endothermic reactions between \( \text{H}_2 \) and \( \text{O} \) and thus the gas temperature has to be high enough to make the reaction effective: this only happens in dense \( (\geq 10^3 \text{cm}^{-3}) \) regions. To our knowledge, there are two classes of situations where \( \text{C}^+ / \text{CO} \) transition dense regions are formed: in dense PDRs (Wolfire, Tielens, & Hollenbach 1990) and behind fast, dissociative J-shocks (Hollenbach & McKee 1989).

3.1. The PDR origin hypothesis

The only known detections of \( \text{CO}^+ \) have come from dense PDR’s where UV from the exciting star creates a large \( \text{C}^+ / \text{CO} \) transition region in the surrounding molecular cloud (Latter, Walker & Maloney 1993; Storzer, Stutzki & Sternberg 1995; Fuente & Martín-Pintado 1997). However, the exciting star of IRAS 16293–2422 has too low a luminosity \( (30 \text{ L}_\odot) \) to excite such emission. Yet, given the evidence that infall is occurring onto this source (Zhou 1995), we consider the possibility that UV from the accretion shock that would form where the infalling gas releases its gravitational energy could excite a PDR responsible for the \( \text{CO}^+ \) emission we detect.

To check this possibility, we ran the PDR model of Wolfire, Tielens & Hollenbach (1990) with the assumption that all \( 30 \text{ L}_\odot \) of radiation is emitted at the accretion shock front in the FUV spectral region and that these photons illuminate the gas at a distance of 20 AU where the density of the gas is assumed to be \( 2 \times 10^8 \text{ cm}^{-3} \) (in agreement with the parameters of the Zhou 1995 model). We find that a shell of thickness 0.1 AU is formed in which \( \text{CO}^+ \) is \( \sim 10^5 \) more abundant than in cold molecular clouds \( (X(\text{CO}^+) \sim 10^{-8}) \), the gas is very warm \( (\sim 2000 \text{ K}) \), and the total \( \text{CO}^+ \) column density is \( 10^{12} \text{ cm}^{-2} \). Although this is a surprisingly high \( \text{CO}^+ \) column density, it is still about 500 times lower than the value we infer from our observations for such a small emitting region. If we take the shell radius to be 700 AU \( (\sim 0.5 \text{ AU}) \) instead of 20 AU, and allow half the FUV flux to reach this radius, then the column density inferred from our observations is only two times larger than the model predicts \( (N(\text{CO}^+)\sim 10^{11} \text{ cm}^{-2} \) in gas of density of \( 10^3 \text{ cm}^{-3} \) and a temperature of \( \sim 120 \text{ K}) \). However, we consider it highly unlikely that FUV radiation could travel so far, given the massive dusty envelope surrounding the central object (seen at millimeter wavelengths, e.g. André et al. 1993). In addition, such a large PDR would predict that the \( \text{O}(60 \mu \text{m}) \) line should be 20 times brighter than observed and that the \( \text{OH} \) lines should be 10 times brighter than observed (although these lines could be absorbed in the cooler outer envelope while \( \text{CO}^+ \) emerges undisturbed since it is not formed in the rest of the envelope).

3.2. The J-shock origin hypothesis

There is a great deal of observational evidence that a strong protostellar wind is blowing from IRAS 16293–2422 (see, e.g., Ceccarelli et al. 1997a; Paper I). Since the central object is still surrounded by its placental envelope it is natural to think that a shock is created when the wind strikes the surrounding medium. If the shock is fast enough \( (\geq 40 \text{ km s}^{-1}) \), the macroscopic quantities of the gas suffer a “jump” in their values and a so-called J-shock is formed (Hollenbach, Chernoff & McKee 1989). The gas temperature is so high at the shock front that molecules are dissociated and only reform when the UV field emitted at the front is shielded (Hollenbach & McKee 1989). In order to produce \( \text{CO}^+ \), the FUV produced by the high temperatures of the J-shock are needed. We ran the J-shock model of
Hollenbach & McKee (1989) and Neufeld & Hollenbach (1994) to obtain estimates of the CO$^+$ column density $N$(CO$^+$) created in the warm gas behind the shock front. We varied three main parameters of the model: the pre-shock gas density $n_0$, the velocity of the shock $v_s$, and finally the pre-shock magnetic field strength $B_0$. The CO$^+$ column density depends strongly on the magnetic field and shock velocity, but very little on the pre-shock density. For high ($\sim 1$ mG) magnetic fields and/or high shock velocities ($\sim 200$ km s$^{-1}$) we find $N$(CO$^+$) $\sim 10^{13}$ cm$^{-2}$. The most favorable case is $v_s=100$ km s$^{-1}$, $n_0=10^5$ cm$^{-3}$ and $B_0=1.6$ mG, for which we obtain an estimate of $N$(CO$^+$)$=1.2\times10^{13}$ cm$^{-2}$. The CO$^+$ has a peak abundance of 2.5x10$^{-9}$ where the gas temperature is about 2000K and the gas density is $10^5$ cm$^{-3}$. Assuming that the emission originates in a 6″x6″ ($r=500$ AU) region, the computed N(CO$^+$) is only a factor of 5 lower than observed. Considering the uncertainties in both the modeling and the observations we consider this as a rather encouraging agreement. The model predicts that the post-shock gas cooling is dominated by the emission of the OI(63μm) line, which would be about ten times the observed strength (Paper I). However, the OI(63μm) line, as already mentioned previously, is expected to be easily absorbed by the surrounding material, so we do not see this as a real discrepancy. Finally, we briefly discuss the role and value of the predicted magnetic field. Although a magnetic field is not necessary for the existence of a J-shock, its strength limits the maximum compression achieved in the post-shock gas, and consequently it affects the post-shock region structure and line emission. In particular a large magnetic field produces a lower post-shock density, and less efficient shielding of the UV photons causing the C$^+/CO$ transition region to expand and leading to a larger CO$^+$ column density (see Hollenbach & McKee 1989). Our CO$^+$ observations are consistent with the presence of a magnetic field of $\sim 1$ mG at a distance of 500 AU from the central object. Compared with the observations of the magnetic fields in cold cores ($\sim 10\mu$G; see, e.g., Troland et al. 1996) this seems a rather high value. However, very recently Ray et al. (1997) reported the detection of a magnetic field of several gauss at a distance of 20 AU from T Tau S. Scaling as $r^{-2}$ would result in a field of several mG at 500 AU.

4. CONCLUSIONS

We have observed, for the first time, high-N rotational transitions of CO$^+$ molecule in the interstellar medium. Their detection was unpredicted. We derived upper limits to the gas temperature ($\geq 300$ K) and CO$^+$ column density ($\geq 7\times10^{13}$ cm$^{-2}$) by using LTE and optically thin approximations and assuming a filling factor equal to one. Two possible origins are proposed for this CO$^+$ emission. It may in principle originate in the very dense PDR region that would form close to the infall accretion shock. However, in practice the modeling (Wolfire, Tielens & Hollenbach 1990) shows that this would require that half of the bolometric luminosity be emitted as FUV photons which reach a radius of $\sim 700$ AU from the source unabsorbed. Given the large amount of dust in the envelope of IRAS16293-2422, this seems rather un-

reasonable.

The most plausible explanation is that the CO$^+$ emission originates in a strong, dissociative J-shock occurring about 500 AU from the central object. Comparison of the observed CO$^+$ column density with the predictions of the Hollenbach & McKee (1989) model, suggests the presence of a large magnetic field ($\sim 1$ mG) at such a distance.

Future ground-based observations of the CO$^+$ submillimeter transitions should help to shed light on the origin of this detection and either add support to, or reject the J-shock origin for the high-N CO$^+$ transitions.

REFERENCES


Rosmus P., Werner H.J., 1982 Molec. Phys. 47, 661


Question from Christian Muller

Question: What will be the spectral resolution of the new ground based CO⁺ observations?

Answer: The spectral resolution will be about 0.2 km/s much better than that we have with the LWS grating (1500 km/s).

Question from Martin Harwit

Question: Did you look at charge exchange as a formation mechanism? In comets CO⁺ is produced through charge exchange, which has a large cross section ≈ 10⁻¹⁵ cm² for formation?

Answer: No, we didn’t. We will check if this formation mechanism could be relevant for this source.

Question from Pierre Cox

Question: Have you observed the CO⁺ transitions in the millimeter range towards IRAS 16253-2422?

Answer: Not yet, but we have asked for ground-based observations on IRAM in this range for this source.
Session 3: Molecular Clouds and PDRs (Spacecraft Commissioning Phase)