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Journal Item

Astron. Astrophys. 331, L17–L20 (1998)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

ISO Detection of CO^+ toward the protostar IRAS 16293–2422 ⋆

C. Ceccarelli[1,2], **E. Caux**[3], **M. Wolfire**[4,5], **A. Rudolph**[6], **B. Nisini**[2], **P. Saraceno**[2], **and G.J. White**[7]

[1] Laboratoire d'Astrophysique, Observatoire de Grenoble - BP 53, F-38041 Grenoble cedex 09, France
[2] CNR-IFSI Area di Ricerca Roma - Tor Vergata, I-00133 Roma, Italy
[3] CESR CNRS-UPS, BP 4346, F-31028 Toulouse cedex 04, France
[4] University of Maryland, College Park, MD, 20742, USA
[5] Towson University, Department of Physics, Towson, MD 21252 USA
[6] Harvey Mudd College, Department of Physics, Claremont, CA 91711 USA
[7] Queen Mary and Westfield College - University of London, Mile End Road - London E1 4NS, UK

Received 7 November 1997 / Accepted 9 December 1997

Abstract. In this letter we report the detection of eight high-N rotational transitions of CO^+ towards a low mass protostar, IRAS 16293−2422. The source was observed with the Long Wavelength Spectrometer on board the Infrared Space Observatory. This is the first time that CO^+ 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^+ 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 ~ 500 AU from the star is the origin of the CO^+ emission. This model predicts CO^+ column densities in rough agreement with the observations if the magnetic field is ~ 1 mG and the shock velocity is 100 km s^{-1}.

Key words: ISM: jets and outflows – ISM: individual: IRAS 16293−2422 – stars: formation – infrared: ISM: lines

1. Introduction

The first claim of the detection of the CO^+ ion was at millimeter wavelengths (Erickson et al. 1981) and proved to have been a false alarm (Blake et al. 1984). More recently the search for the ionic form of the most abundant molecule (after H_2) in space was rewarded with the detection of the N=2→1 J=5/2→3/2 line towards several "classical" PhotoDissociated Regions (PDR; Tielens & Hollenbach 1985), including M17SW, NGC7027 (Latter, Walker & Maloney 1993, Latter & Walker 1995), the Orion Bar (Storzer, Stutzki & Sternberg 1995), and the reflection nebula NGC 7023 (Fuente & Martin-Pintado 1997). All these detections of CO^+ were interpreted as coming from CO^+ originating in dense PDRs.

The CO^+ molecule has a $^2\Sigma$ 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^+ rotational transitions are at similar wavelengths, although the CO^+ spontaneous emission coefficients are hundreds times greater than those of CO. However, the expected abundance of CO^+ in interstellar clouds is 10 orders of magnitude lower than CO, so that to be detected, a huge amount of CO^+ has to be present. We present in this Letter the detection of eight CO^+ lines, namely the rotational transitions from N=14→13 to N=21→20, towards the low-luminosity protostar IRAS 16293−2422.

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 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

Send offprint requests to: Cecilia.Ceccarelli@obs.ujf-grenoble.fr

⋆ 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.

Table 1. Parameters of the observed CO^+ lines.The statistical error is $0.2 \cdot 10^{-12}$erg s^{-1} cm^{-2}. E_{up} is the energy of the upper level.

λ_{teo} (μm)	λ_{obs} (μm)	Flux (10^{-12}erg s^{-1} cm^{-2})	Transition	E_{up} (cm^{-1})
181.77	181.91	0.7	14-13	412
169.67	169.66	1.9	15-14	471
159.10	159.10	1.2	16-15	534
149.76	149.66	1.2	17-16	601
141.48	141.58	0.8	18-17	672
134.06	134.01	0.7	19-18	746
127.39	127.45	0.6	20-19	825
121.36	121.27	0.7	21-20	907

OI(63μm) 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 (Ceccarelli 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 45μm to 198μm range, in addition to the CO^+ lines reported here (Ceccarelli et al. 1997b, hereinafter Paper I): the CO rotational transitions from J_u=14 to J_u=25, several H_2O and OH rotational lines, as well as the OI(63μm) and CII(157μm) 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_2O and OH lines probably originate in the same region. On the contrary, the CII(157μm) line comes from the tenuous ($\sim 2 \cdot 10^3$ cm^{-3}) gas illuminated by a weak UV field ($G_0 \sim 6$) at the skin of the parental cloud.

2. Observations and results

IRAS 16293−2422 was observed during Revolution 85 (10 February 1996) with the LWS (Clegg et al. 1996). Spectra covering the 45μm to 198μm range were obtained with a spectral resolution $\sim$ 200 and calibrated with Uranus. The beam size was approximately 80″ (Swinyard et al. 1996). The spectrum was relatively free from fringing problems: 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. 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.

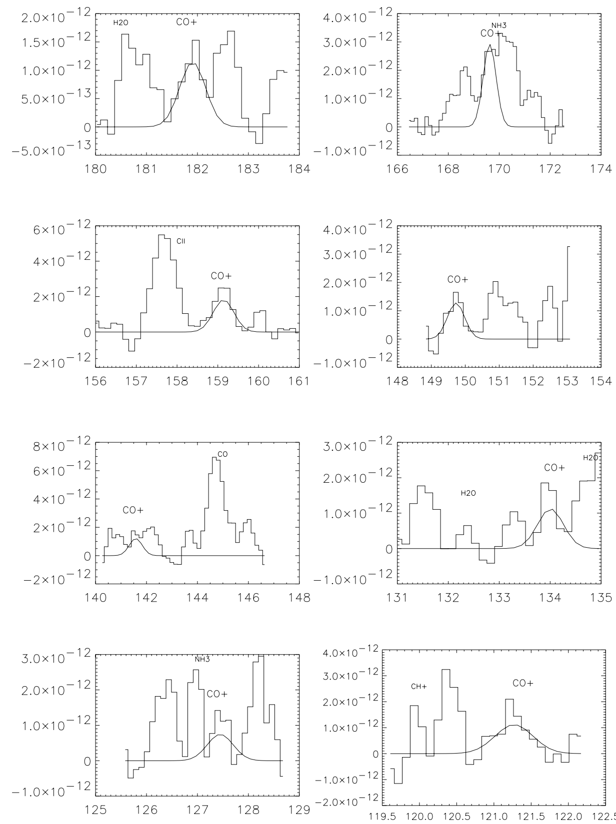

Fig. 1. Observed CO^+ lines including transitions from N=14→13 (upper left) to N=21→20 (lower right). Fluxes are in erg s^{-1} cm^{-2} and wavelengths are in μm. The solid curves show the gaussian best-fits obtained assuming a linewidth equal to the spectral resolution element, 0.6μm. Identified lines in the range of each plot are also marked.

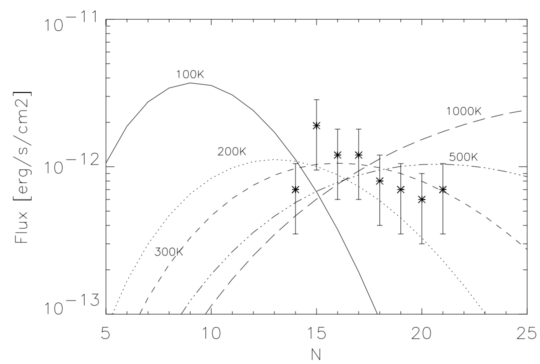

Fig. 2. The observed CO^+ line fluxes versus N_{up}. The curves in the plot show the theoretical spectra obtained in the LTE and optically thin approximation, for different temperatures. The error bars take into account a factor two of uncertainty in the estimated fluxes.

Fig. 1 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.

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(CO^+) depends on the unknown filling factor: the lower limit on N(CO^+) obtained by assuming a filling factor of unity and T_{gas}=1000 K is $\sim 7 \cdot 10^{10}$ cm^{-2}. This value scales almost linearly with T_{gas}. However, since the 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(CO^+) is likely to be substantially higher than this value. Integrating the lines fluxes to find the total luminosity of the CO^+ lines and comparing with the similar lines of CO reported in Paper I shows that the CO lines are only five times more luminous than CO^+ lines. No existing model has ever predicted such a large luminosity for this molecular ion.

In cold molecular clouds the CO^+ abundance is predicted to be very low ($\sim 10^{-15}$) as it is efficiently destroyed by reactions with H_2, and formed at low rates via the ionisation of CO by cosmic rays. Standard chemistry (see for example the UMIST database, Millar et al. 1997) predicts a substantial CO^+ abundance enhancement only in regions where CO^+ formation occurs via the reaction of C^+ with OH (or O_2), namely in regions where the C^+ ion and OH (or O_2) molecule are *simultaneously* present. These conditions are found in *dense* C^+/CO transition regions, where a far-UV field photodissociates the CO molecules and photoionises the atomic carbon, but at the same time is sufficiently shielded by the dense medium to allow the formation of OH. The production of OH proceeds via endothermic reactions between H_2 and O and thus the gas temperature has to be high enough to make the reaction effective: this only happens in dense ($\geq 10^5$cm^{-3}) regions. To our knowledge, there are two classes of situations where C^+/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 CO^+ have come from dense PDR's where UV from the exciting star creates a large C^+/CO transition region in the surrounding molecular cloud. However, the exciting star of IRAS 16293−2422 has too low a luminosity (30 $L_\odot$) 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 CO^+ emission we detect.

To check this possibility, we ran the PDR model of Wolfire, Tielens & Hollenbach (1990) with the assumption that all 30$L_\odot$ 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 $2 \cdot 10^8$ 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 CO^+ is $\sim 10^6$ more abundant than in cold molecular clouds (X(CO^+) $\sim 10^{-9}$), the gas is very warm ($\sim$ 2000K), and the total CO^+ column density is 10^{12} cm^{-2}. Although this is a surprisingly high 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 (=8$''$) 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(CO^+)=10^{12} cm^{-2} in gas of density of 10^6cm^{-3} and a temperature of $\sim$ 1200K). 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 OI(63μm) line should be 20 times brighter than observed and that the OH lines would be 15 times brighter than observed (although these lines could be absorbed in the cooler outer envelope while 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 (≥ 40 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 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 results of the model predictions are shown in Fig. 3. 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^+) $\sim 10^{12}$cm^{-2}. Taking the most favorable case from Fig. 3, i.e. v_s=100 km s^{-1}, n_0=10^5cm^{-3} and

B_0=1.6 mG, we obtain an estimate of N(CO^+)=$1.2{\cdot}10^{12}$cm^{-2}. The CO^+ has a peak abundance of $2.5{\cdot}10^{-9}$ where the gas temperature is about 2000K and the gas density is 10^6cm^{-3}. Assuming that the emission originates in a $6''{\times}6''$ (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($63\mu m$) line, which would be ten times the observed strength (Paper I). However, the OI($63\mu m$) 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. This apparent discrepancy may be due to the intrinsic way of measuring the magnetic field in cold cores: namely, the Zeeman effect of radio transitions of molecules (OH, HI or CN) which usually traces the cold (and outer) material. In addition, the observations are obtained with relatively large beamsizes ($\geq 3'$; Troland et al. 1996) with respect to a 500 AU scale.

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 ($\geq 7 \cdot 10^{10}$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 unreasonable.

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.

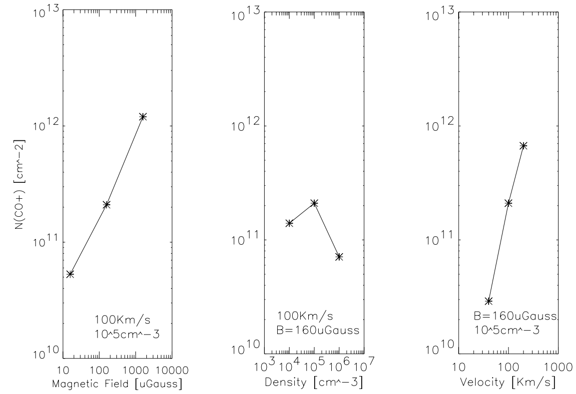

Fig. 3. The CO^+ column density N(CO^+) versus the pre-shock magnetic field strength B_0 (left panel), pre-shock density n_0 (central panel) and shock velocity v_s (right panel).

Planned ground-based observations of the CO^+ submillimeter transitions [1] 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.

Acknowledgements. CC wishes to thank A.Castets for the many generous discussions on the subject. We also wish to thank D.Hollenbach for providing us with his code.

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[1] Extrapolating from the high-N observations we estimate a detectable (integrated) signal of about 10 K km s^{-1}