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VIBRATIONALLY EXCITED CS: A NEW PROBE OF CONDITIONS IN YOUNG PROTOSTELLAR SYSTEMS

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ABSTRACT

We present the first detection of vibrationally excited $C^{32}S$ $J = 10 \rightarrow 9$ and $J = 7 \rightarrow 6$ emission toward a young stellar object. Toward IRAS 16293−2422, the vibrationally excited $C^{32}S$ emission is redshifted ~3.9 km s^{-1} from the systemic velocity of the core. The emission must arise in warm ($T \gtrsim 1000$ K), dense ($n \gtrsim 10^{11}$–10^{12} cm^{-3}) gas. The most plausible origin for the emission appears to be self-gravitating instabilities in a protostellar accretion disk, which produce waves and shocks.

Subject headings: binaries: general — stars: individual (IRAS 16293−2422) — stars: pre–main-sequence

1. INTRODUCTION

The vast majority of the molecular rotation lines observed at millimeter wavelengths in the interstellar medium are associated with the lowest vibrational state ($v = 0$). However, several vibrationally excited molecules have been detected in the ISM (Turner 1987). For vibrational excitation to occur, these molecules must be in regions which are warm and dense (perhaps associated with a shock) or illuminated by intense near-infrared radiation. Since these excitation requirements are expected to be fulfilled only in very compact regions close to protostellar/young stellar sources, vibrationally excited molecules with submillimeter/millimeter-wave rotational transitions should make excellent probes of the physical conditions very near embedded infrared sources.

An excellent candidate source for such observations is IRAS 16293−2422 (hereafter IRAS 16293). It is located in the eastern streamer region of the Rho Ophiuchi molecular cloud complex; is enshrouded in a cold, dense dust and molecular gas core; and possesses an unusual quadrupolar outflow (Walker et al. 1986; Mundy, Wilking, & Myers 1986; Wootten & Loren 1987; Walker 1988). Interferometric observations (Wootten 1989; Mundy et al. 1992; Walker et al. 1993) indicate that IRAS 16293 is a young binary or protobinary system with a slowly rotating circumbinary disk of material; there are two millimeter continuum sources separated by $\sim 10^{16}$ cm.

In this *Letter* we present the first detections of the $v = 1$, $C^{32}S$ $J = 10 \rightarrow 9$ and $J = 7 \rightarrow 6$ transitions toward a young stellar object. By comparing these $v = 1$ transitions with each other and to the corresponding $v = 0$ transitions, we are able to determine the conditions in the emission region.

2. OBSERVATIONS

We have detected the vibrationally excited $C^{32}S$ ($v = 1$) $J = 10 \rightarrow 9$ and $J = 7 \rightarrow 6$ transitions toward IRAS 16293 using the 10.4 m CSO. We also obtained an upper limit to the temperature of the $v = 1$, $J = 5 \rightarrow 4$ line. The initial observation of the $v = 1$, $C^{32}S$ $J = 7 \rightarrow 6$ line was made during July of 1990. The $v = 1$ $C^{32}S$ $J = 10 \rightarrow 9$ and $J = 5 \rightarrow 4$ lines were observed in 1994 March. The spectra were obtained using low-noise SIS receivers (Walker et al. 1992; Ellison et al. 1991) and an AOS with a spectral resolution of 50 kHz (Serabyn 1990). The atmospheric optical depth during these observations was excellent, with a typical value at 225 GHz of ≤ 0.05. The frequency of each transition and the corresponding telescope beam size and main beam efficiency during the observations are listed in Table 1.

The $v = 1$, $C^{32}S$ $J = 7 \rightarrow 6$ and $J = 10 \rightarrow 9$ lines are shown in Figures 1*a* and 1*b*. The rms noise level per channel in Figures 1*a* and 1*b* are 0.22 and 0.55 K, respectively. The $v = 1$, $C^{32}S$ $J = 7 \rightarrow 6$ line has a main beam brightness temperature of 0.13 K, and a linewidth of 3.8 km s^{-1}, comparable to that observed in the $v = 0$ transitions. The $v = 1$, $J = 10 \rightarrow 9$ main beam brightness temperature is 1.44 K, with a linewidth of 0.63 km s^{-1}, ~6 times narrower than the $v = 1$, CS $J = 7 \rightarrow 6$ line. Longer integration times are required to determine whether this difference in linewidth is real or simply an artifact of the lower signal-to-noise ratio of the $v = 1$, $J = 10 \rightarrow 9$ data. Both transitions occur at a velocity of 7.9 km s^{-1}, which corresponds to a redshift of 3.9 km s^{-1} from the systemic velocity of the source ($V_{\rm lsr} = 4$ km s^{-1}). With a single line, such a velocity offset could suggest a line misidentification, but with two lines, both at a similar velocity offset, it is more likely that the identification is correct, and that the velocity shift is kinematic. Finally, the upper limit obtained on the $v = 1$, $J = 5 \rightarrow 4$ line was 0.025 K.

3. DISCUSSION

3.1. *Excitation of the $v = 1$ $C^{32}S$ Emission*

The $v = 1$, $J = 10 \rightarrow 9$ line from IRAS 16293 has a peak antenna temperature approximately 10 times larger than the $v = 1$, $J = 7 \rightarrow 6$ line. With the main beam efficiencies from Table 1, we find that the ratio of main beam temperatures is $T_{\rm mb}(10\text{–}9)/T_{\rm mb}(7\text{–}6) \approx 12$. Such a large ratio of antenna temperatures implies that the emission must be optically thin and

TABLE 1

Observed Lines

Species	Transition	Frequency (GHz)	Beam Size	η_{mb}
$C^{32}S$......	$v = 1, J = 5 \rightarrow 4$	243.160773	30″	0.75
$C^{32}S$......	$v = 1, J = 7 \rightarrow 6$	340.398080	22	0.60
$C^{32}S$......	$v = 1, J = 10 \rightarrow 9$	486.201096	15	0.55

at high temperature ($h\nu/kT \ll 1$ for the observed lines). Under the assumption that the lower rotational levels are in LTE (which is undoubtedly a good assumption—see below), and assuming that $h\nu/kT_{ex} \ll 1$ for the relevant transitions, we can write the line center optical depth for rotational transition $j \rightarrow i$ as

$$\tau_{ji} = \frac{c^3 h}{8\pi\nu_{ji}^2} \frac{A_{ji}}{kT_{ex}} \frac{(2j+1)}{(2i+1)} \frac{N_i}{\Delta V}, \tag{1}$$

where A_{ji} is the Einstein A-coefficient, N_i is the total column density in the level $J = i$, and ΔV is the line FWHM. In the high-temperature, optically thin limit, the observed peak main beam temperature will just be $T_{mb} = T_{ex}\,\tau_v\,\Omega_s/\Omega_A$, where Ω_s, Ω_A are the source and antenna solid angles. Under the assumption that the source size is the same for both transitions, and assuming that $\Omega_A \propto \nu^{-2}$, the ratio of main beam temperatures for two transitions $j \rightarrow i$ and $n \rightarrow m$ is

$$\frac{T_{mb}(ji)}{T_{mb}(nm)} = \frac{A_{ji}}{A_{nm}} \frac{(2j+1)}{(2i+1)} \frac{(2m+1)}{(2n+1)} \frac{N_i}{N_m}. \tag{2}$$

Evaluating this expression for the $v = 1$, $J = 10 \rightarrow 9$ and $v = 1$, $J = 7 \rightarrow 6$ transitions, and assuming LTE in the high-temperature limit, so that N_9/N_6 is just the ratio of statistical weights, we get $T_{mb}(10\text{–}9)/T_{mb}(7\text{–}6) = 4.2$. This is substantially *smaller* than the observed ratio. This difference is probably due to a combination of calibration uncertainties, low SNR, and small ($\lesssim 5''$) pointing offsets between the observed frequencies.

Our upper limit to the $v = 1$, $J = 5 \rightarrow 4$ line is completely consistent with the detection of the $v = 1$, $J = 7 \rightarrow 6$ line. The fact that we do not see bright $v = 0$ lines over the velocity range of the $v = 1$ emission [which will be stronger by the ratio $N(v = 0)/N(v = 1) > 1$] indicates that the optical depth of the cold gas at larger radii must be quite large, even at $v_{LSR} = 7.9$ km s^{-1}.

The size of the $v = 1$ emitting region must be substantial. We can write the main beam temperature as (we will refer all discussion to the $v = 1$, $J = 7 \rightarrow 6$ line from now on, due to the better signal-to-noise ratio and lower calibration uncertainty):

$$T_{mb} = 0.17\left(\frac{T_{ex}}{2000\ \mathrm{K}}\right)\left(\frac{\tau_v}{0.1}\right) r_{15}^2, \tag{3}$$

where $10^{15} r_{15}$ cm is the radius of the emitting region. With the observed $T_{mb} \approx 0.13$ K, we can solve for the size scale as $r_{15} = 0.9[(2000/T_{ex})(0.1/\tau_v)]^{1/2}$. Even if we were to assume that the emission is optically thick (which is inconsistent with the measured line ratios), the source radius could be smaller by only a factor of a few for plausible source brightness temperatures.

The vibrational levels can, in principle, be excited through collisions or infrared pumping, with the infrared radiation arising from the central stellar object and/or a dusty disk. The large size scale of the emitting region and the low bolometric luminosity of IRAS 16293 ($L \sim 23\ L_\odot$) makes radiative pumping models quite untenable, however. Radiative pumping can produce only a substantial population in $v = 1$ if the brightness temperature of the radiation field around the wavelength of the $v = 1\text{–}0$ bandhead ($\lambda \sim 7.9\ \mu$m), as seen by the molecules, is comparable to $h\nu/k$, the temperature of $v = 1$ above ground (Scoville, Krotkov, & Wang 1980). Assuming a blackbody spectrum with temperature $T_{BB} = 2000$ K around 7.9 μm, the required source luminosity is $L_B \sim \nu L_\nu \sim 1.7 \times 10^4 r_{15}^2\ L_\odot$, which is roughly three orders of magnitude larger than the observed luminosity. Hence radiative pumping by the near-infrared radiation field from either the protostar itself or a warm disk is ruled out as an excitation mechanism. For the rest of this paper we assume the $v = 1$ lines are collisionally excited.

At the densities necessary to produce an appreciable population in $v = 1$ (see below), we can assume the rotational levels are in LTE, with the rotational partition function given by $J_T^2 = kT/E_0$; for $C^{32}S$ the rotational constant $E_0 = 1.176k$. No direct measurements of the rate coefficients for collisional excitation of the vibrational levels appear to exist. We have used the general expression for vibrational relaxation time determined by Millikan & White (1963) (cf. Scoville et al. 1980) from which we obtain (for collisions with H_2)

$$\gamma_{10} = 2.56 \times 10^{-11} T_3 e^{-3.591/T_3^{1/3}}\ \mathrm{cm^3\ s^{-1}} \tag{4}$$

for the $v = 1\text{–}0$ deexcitation rate. At $T \sim 1000\text{–}2000$ K, the $C^{32}S$ molecules will be broadly distributed over the rotational levels, peaking aproximately at $J \sim 30\text{–}50$. The appropriately weighted A-value for $v = 1\text{–}0$ is $A_{10} \sim 15\ \mathrm{s^{-1}}$. From equation (4) we then get that the critical density, above which the $v = 1$ level population approaches the LTE value, is $n_{H_2}^{cr} \sim 5 \times 10^{12}$ cm^{-3} at 2000 K. The excitation rate coefficient for collisions

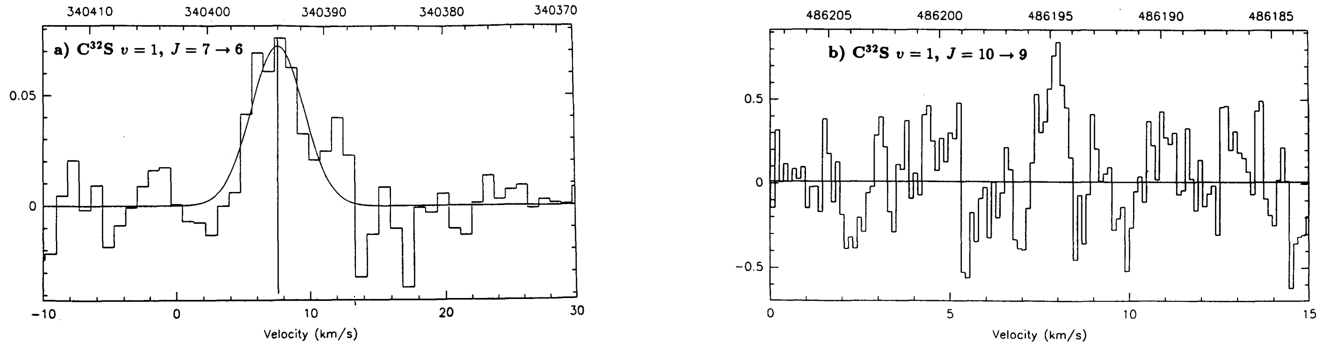

Fig. 1*a*

Fig. 1*b*

Fig. 1.—Vibrationally excited $C^{32}S$ lines toward IRAS 16293. (*a*) The $v = 1$, $C^{32}S$ $J = 7 \rightarrow 6$ line. (*b*) The $v = 1$, $C^{32}S$ $J = 10 \rightarrow 9$ line.

with atomic hydrogen is ~ 100 times larger than for collisions with H_2 at $T \sim 1000$–2000 K (Neufeld & Hollenbach 1994); if there is a significant fractional abundance of atomic hydrogen, then the required density could be significantly less. In addition, the optical depths of the $v = 1$–0 lines may be $\tau \sim 10$, which will reduce the critical densities by $1/\tau$. In any case, production of detectable $v = 1$ emission clearly requires gas that is both warm ($T \gtrsim 1000$ K) and very dense ($n \gtrsim 10^{11}$–10^{12} cm^{-3}). In a protostellar object the most likely place for such conditions to exist over size scales of $\sim 10^{15}$ cm is in a circumstellar disk. If the 3.9 km s^{-1} velocity offset in the $v = 1$ $C^{32}S$ lines originates in a circumstellar disk due to gravitational motion (e.g., rotation or infall), then the inferred size scale of the emitting region is $r \sim 10^{15} M_c/M_\odot$ cm, where M_c is the mass of the central object. The combined mass of the stellar cores is estimated to be $< 1\ M_\odot$ (Walker et al. 1986, 1993; Mundy et al. 1992).

3.2. *The Excitation Mechanism: A Dynamically Active Disk?*

The large observed luminosities in the $v = 1$ lines (i.e., the large inferred size scale of the emitting region) are difficult to explain. As we noted above, excitation by radiative pumping is ruled out. Furthermore, dust continuum observations show that the circumbinary disk has extremely high column densities: Mezger et al. (1990) find the central 10″ core region of IRAS 16293 is optically thick ($\tau \sim 0.72$) at 1300 μm, with an inferred column density over the central 10 arcsec^2 core of $N_H = 5.1 \times 10^{25}$ cm^{-2}. Although this naturally provides the very high densities needed for excitation of the $v = 1$ lines, the high temperatures which are necessary cannot be characteristic of the whole column through the disk, as the optically thick disk would then radiate far more luminosity than is observed in the far-IR and millimeter continuum, by orders of magnitude. This suggests that only a very small fraction ($\sim 10^{-3}$ to 10^{-4}) of the total disk column has been heated to such temperatures. This is a natural result of shock heating, as the column density of the warm shocked region is unlikely to exceed $N \sim 10^{21}$ cm^{-2} (Neufeld & Hollenbach 1994).

It is possible for a shocked region to have a large enough optical depth in the $v = 1$ lines to explain the observed emission, provided the CS abundance is substantial: the optical depth in the $v = 1, J = 7 \rightarrow 6$ line is

$$\tau_{7-6} = 0.063 \frac{f_1}{T_3^2} \left(\frac{x_{\rm CS}}{10^{-6}}\right) \frac{N_{21}}{\Delta V_5} , \qquad (5)$$

where f_1 is the fraction of all CS in $v = 1$, $x_{\rm CS}$ is the fractional abundance of CS, N_{21} is the total hydrogen column $N_H/10^{21}$ cm^{-2} in the emitting region, and ΔV_5 is the linewidth in km s^{-1}. If the lowest vibrational levels are approximately in LTE, $f_1 \sim e^{-1.8/T_3}$. CS abundances as large as 10^{-7} have been measured in dense cloud cores (Irvine, Goldsmith, & Hjalmarson 1987). However, there are other difficulties. One attractive possibility is that the emission arises in an accretion shock, which marks the point at which infalling material is incorporated into the accretion disk of the protostar. However, since the infall velocity is only a few km s^{-1} at 10^{15} cm, the postshock temperatures are only just high enough to excite the $v = 1$ lines, so there is very little postshock compression of the gas. (For such low shock velocities, $\lesssim 15$ km s^{-1}, only a small fraction of the molecules are dissociated: Neufeld & Hollenbach 1994). This means the preshock density of the infalling gas must be large enough to excite the CS into $v = 1$, i.e., of order 10^{11} cm^{-3}. This requires a prohibitively large mass infall rate:

$$\dot{M} = 1.7 \times 10^{-2} r_{15}^2 v_6 n_{11}\ M_\odot\ {\rm yr}^{-1} , \qquad (6)$$

where the shock speed $v_s = 10 v_6$ km s^{-1} and the preshock density is $n = 10^{11} n_{11}$ cm^{-3}. The shock luminosity is

$$L_s = \tfrac{1}{2} \dot{M} v_s^2 = 140 r_{15}^2 n_{11} v_6^2\ L_\odot \qquad (7)$$

which, for $v_6 \sim 0.5$, is somewhat greater than the observed luminosity of the system.

The very high mass infall rates are alleviated if the shock is actually being driven into the protostellar disk itself. In this case the densities are already expected to be very high, and the mass flux represents the flux of material through the shock front(s), not actual accretion onto the disk. One possibility is that a shock is being driven through the disk by the protostellar wind which drives the outflow. However, this requires an enormous ram pressure in the wind, with a consequently large mass and momentum flux, exceeding by orders of magnitude any known protostellar wind: the minimum momentum flux (assuming the wind solid angle is just that of the shocked area) is

$$\dot{M} v = 0.17 r_{15}^2 v_6^2 n_{11}\ M_\odot\ {\rm yr}^{-1}\ {\rm km\ s}^{-1} . \qquad (8)$$

Such a large momentum and mass flux also implies a necessarily large mass infall rate in order to fuel it, leading to the same difficulty as for an accretion shock.

We are left with the possibility that the shock is due to internal dynamical processes in the disk itself. A plausible source for such shocks is self-gravitating instabilities in the disk, such as the eccentric $m = 1$ instability discussed by Adams, Ruden, & Shu (1989). The disk itself may be unstable to the generation of such density waves (Adams et al. 1989; Shu et al. 1990), or they may be excited by a companion star either external to or embedded in the disk (Ostriker, Shu, & Adams 1992). The theory of such waves, elegantly developed in the above papers, is not yet capable of making detailed predictions for the resulting physical conditions in the disk. Here we note only the following points:

1. The IRAS 16293−2422 system appears ideally suited for the generation of these instabilities, due to the large apparent disk-to-central mass ratios (the total mass of gas and dust in circumbinary and circumstellar material is $\sim 1\ M_\odot$, while the protostellar cores appear to be $< 1\ M_\odot$ [Mundy et al. 1992]). The binary nature of the system may either drive the density waves (Ostriker et al. 1992) or result from the growth of $m = 1$ instabilities (Adams et al. 1989).
2. We can estimate the order of magnitude of global energy transport through the disk resulting from the instability using equation (A11) of Shu et al. (1990); this is typically of the order of 1 $L_\odot$, but could be increased by an order of magnitude by increasing the disk radius and/or mass. Thus the energetics are at least plausibly adequate for generating the $v = 1$ emission. The lopsided nature of the density waves also explains why the velocity shift of the $v = 1$ lines is asymmetric.

This explanation raises the possibility of probing the internal disk dynamics in such systems using the vibrational excited lines of species such as CS.

4. SUMMARY

We have observed the $v = 1$, $C^{32}S$ $J = 10 \rightarrow 9$ and $J = 7 \rightarrow 6$ transitions toward IRAS 16293−2422. The $v = 0$,

$C^{32}S$ and $C^{34}S$ $J = 10 \rightarrow 9$ lines were also observed. An excitation analysis of these lines suggests the $v = 1$ emission arises in hot (1000–2000 K), dense (10^{11}–10^{12} cm^{-3}) gas located approximately 10^{15} cm from one of the stellar cores. We find the most likely excitation mechanism for this emission to be self-gravitating instabilities in a protostellar accretion disk, which produce waves and shocks. Eccentric ($m = 1$) instabilities are plausible candidates. These results suggest vibrationally excited CS lines can serve as an effective probe of accretion disk conditions in young stellar objects.

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