

DETECTION OF THE 2165 INVERSE CENTIMETER (4.619 MICRON) XCN BAND  
IN THE SPECTRUM OF L1551 IRS 5STEPHEN C. TEGLER,<sup>1,2</sup> DAVID A. WEINTRAUB,<sup>2,3</sup> LOUIS J. ALLAMANDOLA,<sup>4</sup> SCOTT A. SANDFORD,<sup>4</sup>  
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## ABSTRACT

We report the detection of a broad absorption band at  $2165\text{ cm}^{-1}$  ( $4.619\text{ }\mu\text{m}$ ) in the spectrum of L1551 IRS 5. New laboratory results over the  $2200\text{--}2100\text{ cm}^{-1}$  wavenumber interval ( $4.55\text{--}4.76\text{ }\mu\text{m}$ ), performed with realistic interstellar ice analogs, suggest that this feature is due to a CN-containing compound. We will refer to this compound as XCN. We also confirm the presence of frozen CO (both in nonpolar and polar matrices) through absorption bands at  $2140\text{ cm}^{-1}$  ( $4.67\text{ }\mu\text{m}$ ) and  $2135\text{ cm}^{-1}$  ( $4.68\text{ }\mu\text{m}$ ). The relative abundance of solid-state CO to frozen  $\text{H}_2\text{O}$  is  $\sim 0.13$  while the abundance of XCN seems comparable to that of frozen CO.

*Subject headings:* infrared: interstellar: lines — ISM: individual (L1551 IRS 5) — ISM: molecules — line: identification

## 1. INTRODUCTION

Mid-infrared spectroscopic studies of protostars embedded in dense molecular clouds show the presence of interstellar ices and dust (Willner et al. 1982; Tielens 1989). The ices are known to contain  $\text{H}_2\text{O}$ ,  $\text{CH}_3\text{OH}$ , CO, and  $\text{CH}_4$  (Lacy et al. 1984; Allamandola & Sandford 1988; Lacy et al. 1991; Tielens et al. 1991; Allamandola et al. 1992), and probably  $\text{CO}_2$  (d'Hendecourt & Jourdain de Muizon 1989),  $\text{NH}_3$ , and  $\text{H}_2\text{CO}$ . Additional components of the ices in these clouds are an unidentified CN-containing material (Lacy et al. 1984), as well as carbonyl containing species such as esters, ketones, and aldehydes (Tielens & Allamandola 1987). Observations of comets also show the presence of  $\text{H}_2\text{O}$  (Weaver, Mumma, & Larson 1987),  $\text{CH}_3\text{OH}$  (Bockelee-Morvan et al. 1991), CO (Balsiger et al. 1986),  $\text{CH}_4$  (Larson et al. 1989),  $\text{CO}_2$  (Moroz et al. 1987), and a  $\text{—C}\equiv\text{N}$  containing material (Cruikshank et al. 1991). Although the relative abundance of ice components in protostellar and cometary environments has been under study for several years, few such measurements have been made for material surrounding pre-main-sequence stars. Ices in these environments are intermediate in an evolutionary sense between interstellar ices around protostars and ices in comets; hence, such measurements may provide evidence for determining whether cometary ices formed in situ or whether they survived in abundant enough quantities from interstellar ice reservoirs to permit comet formation without any additional ice evolution. The only relative abundance measurement that exists for frozen material of any type in these pre-main-sequence star environments is for the abundance of CO (Tielens et al. 1991) relative to  $\text{H}_2\text{O}$  (Sato et al. 1990) around L1551 IRS 5.

IRS 5, which is the exciting and driving source for the extremely well separated, prototypical bipolar outflow in the dark cloud L1551, shows a K2 III or later spectral type (Carr, Harvey, & Lester 1987; Stocke et al. 1988), emits a modest bolometric luminosity of  $\sim 40 L_\odot$  (Stocke et al.), likely has a mass of less than  $\sim 2.5 M_\odot$  (Strom et al. 1985) and is shrouded by  $\geq 19$  mag of optical extinction (Snell et al. 1985; Cohen 1975; Davidson & Jaffe 1984) along our line of sight. The outflow lobes are well collimated from within  $0.5'$  out to  $\geq 10'$  ( $\geq 0.5$  pc at a distance of 160 pc) from the central source (e.g., Bieging & Cohen 1985). These results suggest that L1551 IRS 5 is more evolved than typical protostars and is surrounded by a thick circumstellar disk, viewed nearly edge-on to the plane of the sky (Stocke et al. 1988). In fact, Mundt et al. (1985), Carr et al. (1987), and Stocke et al. (1988) have shown that L1551 IRS 5 is probably an FU Orionis star. Keene & Masson (1990) have found that L1551 IRS 5 has a greater than 2000 AU radius envelope surrounding a compact core. They suggest the core, which has a radius of  $45 \pm 20$  AU and a column density of  $\sim 1000\text{ g cm}^{-2}$ , is the preplanetary disk inferred to exist around this star.

FU Orionis stars are a subclass of low-mass pre-main-sequence stars known as T Tauri stars. They are characterized by active growth of the star due to rapid accretion from a massive circumstellar disk (Hartmann et al. 1991). T Tauri stars are observed to have strong stellar winds and outbursts of ultraviolet radiation, especially during the FU Orionis star evolutionary stage. Consequently, icy grains in disks around T Tauri stars may be exposed to high levels of ion bombardment and ultraviolet irradiation.

Laboratory experiments have demonstrated that certain ices undergo chemical changes—some new ice components form and others are destroyed—when exposed to ion bombardment and ultraviolet irradiation. In particular, Moore et al. (1983) and Lacy et al. (1984) report the growth of a broad absorption band centered at  $2165\text{ cm}^{-1}$  ( $4.619\text{ }\mu\text{m}$ ) in the spectra of some laboratory ice mixtures, after exposing the ices to ion bombardment and ultraviolet irradiation, respectively. The laboratory results reported by Lacy et al. showed that the  $2165\text{ cm}^{-1}$  band is produced by irradiating laboratory ice mixtures containing carbon and nitrogen atoms. A carbon atom triply bonded to nitrogen atom has a range of stretching vibrations

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that depend on the group to which it is attached. Because the laboratory  $2165\text{ cm}^{-1}$  band falls in this range Lacy et al. concluded the measured absorption band is due to an unidentified molecule containing a nitrile or iso-nitrile group ( $-\text{C}\equiv\text{N}$  or  $\text{C}\equiv\text{N}-$ , respectively) in a compound they designated as  $\text{X}(\text{C}\equiv\text{N})$ . Alternative identifications for this band have been suggested, namely the CN stretch in the ion  $\text{OCN}^-$  (Grim & Greenberg 1987) and the SiH stretching vibration (Nuth & Moore 1988; Moore, Tanabe, & Nuth 1991). Because (i) the SiH feature seen in published laboratory spectra are too broad ( $50\text{--}200\text{ cm}^{-1}$ , as compared to a value of  $\sim 25\text{ cm}^{-1}$  for the interstellar feature) and the narrowest bands do not match in position ( $2270\text{ cm}^{-1}$  for the laboratory spectra vs.  $2165\text{ cm}^{-1}$  for the interstellar feature) and (ii) the laboratory feature produced by UV irradiation of mixed C- and N-containing ices fits the interstellar feature in both position and width (Lacy et al. 1984; this paper), we prefer an assignment to a CN-containing material and will refer here to the carrier as XCN and the feature as the XCN band.

Very few studies have been done on XCN in astronomical sources. XCN has been positively detected through the  $2165\text{ cm}^{-1}$  band only toward two protostars, W33 A, where it is particularly strong, and NGC 7538 IRS 9 (Lacy et al. 1984). Cruikshank et al. (1991) have identified a similar or identical CN-containing material through the  $4550\text{ cm}^{-1}$  ( $2.2\text{ }\mu\text{m}$ ) overtone on the surfaces of certain asteroids, in the dust around some comets, on the surface of Iapetus, and in the rings of Uranus.

Previously, several groups (see discussion in Cruikshank et al. 1991) showed that absorption bands exist between  $2270$  and  $2040\text{ cm}^{-1}$  ( $4.4\text{--}4.9\text{ }\mu\text{m}$ ) and  $4550\text{--}4350\text{ cm}^{-1}$  ( $2.2\text{--}2.3\text{ }\mu\text{m}$ ) in laboratory reflectance spectra of nitrogen-bearing organic solids. In these studies, the bands were definitely identified with the fundamental and overtone of a  $\text{C}\equiv\text{N}$  stretch. The good match between the astronomical spectra (Lacy et al. 1984), laboratory reflectance spectra (Cruikshank et al. 1991), and irradiated interstellar ice analogs (Lacy et al.; Moore et al. 1983) has been taken as evidence that energetic processing of interstellar ices occurs and plays an important interstellar chemical role. Even though there is limited astrophysical data, XCN has been extensively studied in the laboratory (d'Hendecourt & Allamandola 1986; Grim & Greenberg 1987; Allamandola, Sandford, & Valero 1988).

An understanding of the source and behavior of the  $2165\text{ cm}^{-1}$  ( $4.619\text{ }\mu\text{m}$ ) feature is potentially very important and may help us address questions concerning the formation of stars and planetary systems. For example, is the carrier associated with the general dense cloud medium or is it specifically associated with circumstellar disks known to surround pre-main-sequence stars and embedded protostellar objects? Is it part of the icy or the refractory grain component? Cruikshank et al. (1991) propose that the CN-bearing materials found on solar system bodies may have formed in situ in the solar nebula and are thus part of a refractory material. Observations of XCN in many preplanetary disks could establish whether such materials formed on the surfaces of small bodies in the outer solar system or whether the CN-rich grains formed during an earlier epoch, before accretion produced planetesimals.

No XCN studies have been carried out yet for T Tauri stars. The strong ultraviolet excess associated with FU Orionis stars and the favorable, edge-on morphology of a disk around L1551 IRS 5 suggests the XCN column density along the line of sight to this source could be large enough to be measured.

L1551 IRS 5 therefore offers an excellent opportunity to determine whether icy grains in disks are chemically processed before they accrete to form planetesimals.

In this paper, we report the results of our spectroscopic study of L1551 IRS 5 and present new laboratory results for ice analogs over the  $2200\text{--}2100\text{ cm}^{-1}$  ( $4.55\text{--}4.76\text{ }\mu\text{m}$ ) interval. In our spectrum of L1551 IRS 5, we find strong evidence for a broad absorption band centered near  $2165\text{ cm}^{-1}$ . Our comparison of this spectrum with the spectra of laboratory ice analogs suggests the band is produced by XCN in the disk around this source. We address some of the questions raised by Lacy et al. (1984) about the nature of the carrier. In particular, the new laboratory results relax some of the restrictions on the XCN band carrier presented earlier by Lacy et al. We also confirm the existence of a narrow absorption band at  $2140\text{ cm}^{-1}$  ( $4.67\text{ }\mu\text{m}$ ) produced by frozen CO trapped in a nonpolar matrix and a broader absorption band at  $2135\text{ cm}^{-1}$  ( $4.68\text{ }\mu\text{m}$ ) produced by frozen CO in a polar matrix.

## 2. OBSERVATIONS

We obtained spectra of L1551 IRS 5 using the cooled grating array spectrometer (CGAS) (Tokunaga, Smith, & Irwin 1987) and the Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii, on 1991 October 22–24 UT. CGAS is a grating spectrometer with a linear array of 29 consecutive working InSb detectors. The observations were obtained with a  $2''7$  circular aperture and a  $25''$  north–south chop. The spectrometer, used in second order with grating B, provided a resolving power  $\lambda/\Delta\lambda$  of  $\approx 1300$ . Absolute wavelength calibration was obtained with a krypton lamp inside CGAS. Observations of L1551 IRS 5 were obtained at two grating positions resulting in spectra centered at  $2132\text{ cm}^{-1}$  ( $4.690\text{ }\mu\text{m}$ ) and  $2170\text{ cm}^{-1}$  ( $4.608\text{ }\mu\text{m}$ ) with a seven detector overlap. We obtained eight, 32 s spectra of L1551 IRS 5, four at each grating position. We also obtained six, 16 s spectra of the calibrator BS 1412, three at each grating position. By restricting the air-mass difference between L1551 IRS 5 and BS 1412 to less than 0.10, we ensured that telluric absorption features were accurately removed. To achieve a relative flux calibration, the spectrum of L1551 IRS 5 was multiplied by a  $T = 8190\text{ K}$  blackbody function appropriate for BS 1412.

In Figure 1, we present the calibrated  $2200$  to  $2100\text{ cm}^{-1}$  spectrum of L1551 IRS 5. The narrow and broad frozen CO features centered at  $2140\text{ cm}^{-1}$  and  $2135\text{ cm}^{-1}$ , respectively, and the broad XCN feature centered at  $2165\text{ cm}^{-1}$  clearly are present in the data.

## 3. RESULTS

### 3.1. Astronomical Observations of L1551 IRS 5

The original spectrum of L1551 IRS 5 was converted to the absorbance spectrum shown in Figure 2a using the straight baseline (*dashed line*) drawn in Figure 1. The three high points between  $2193$  and  $2185\text{ cm}^{-1}$  are due to absorption in the bright star spectrum and were not used to define the baseline. Similar absorbance spectra from NGC 7538 IRS 9 (Fig. 2b) and W33A (Fig. 2c) are given for comparison. As laboratory spectra show that the XCN band extends into the tellurically obscured region, the baseline drawn produces a slightly conservative underestimate of the optical depth of both the CO and XCN bands and the width of the XCN band.

Figure 2a shows that the optical depth of the  $2140\text{ cm}^{-1}$  frozen CO feature in the spectrum of L1551 IRS 5 is  $\sim 4$  times

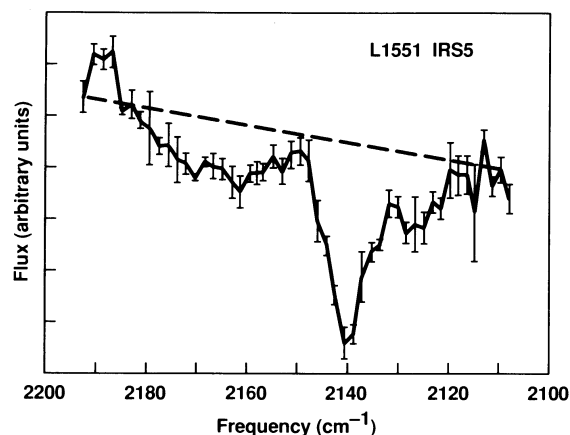


FIG. 1.—The 2200–2100  $\text{cm}^{-1}$  (4.55–4.76  $\mu\text{m}$ ) spectrum of L1551 IRS 5. Flux is given in arbitrary units. The dashed line represents the continuum used to obtain the optical depth spectrum shown in Fig. 2a.

that of the XCN band. This component, assigned to CO frozen in a nonpolar ice, is  $\sim 2$  times as deep as the 2135  $\text{cm}^{-1}$  shoulder which is due to CO in a polar-dominated interstellar ice (Sandford et al. 1988). The CO bands toward L1551 IRS 5 are discussed in detail by Tielens et al. (1991) and will not be treated further here.

Comparison of the 2200 to 2100  $\text{cm}^{-1}$  absorbance spectra of L1551 IRS 5, NGC 7538 IRS 9, and W33 A shows no obvious correlation between the absorbance in the XCN and frozen CO bands. The optical depths of various grain components toward these three objects with the XCN band are summarized in Table 1. Inspection of Table 1 suggests at best only a weak correlation between the XCN band and other ice features. This suggests that the XCN carrier is an independent grain component which is only loosely connected with other known solid constituents.

### 3.2. Laboratory Ice Analogs

Figure 3 shows the spectral evolution in the 2200–2100  $\text{cm}^{-1}$  (4.55–4.76  $\mu\text{m}$ ) region of an interstellar ice analog that was irradiated by ultraviolet light and subsequently warmed under vacuum. The composition of the starting ice was  $\text{H}_2\text{O}:\text{CH}_3\text{OH}:\text{CO}:\text{NH}_3 = 100:50:10:10$ , a composition chosen because its mid-infrared spectrum reproduces the main

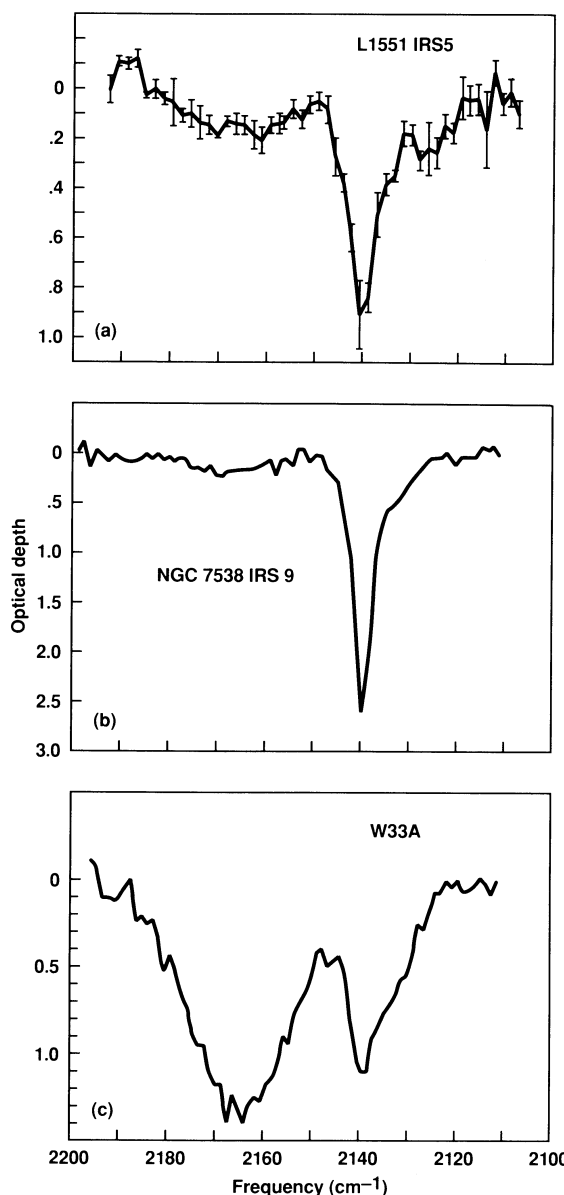


FIG. 2.—The 2200–2100  $\text{cm}^{-1}$  (4.55–4.76  $\mu\text{m}$ ) optical depth spectrum of (a) L1551 IRS 5 compared to those of (b) NGC 7538 IRS 9 and (c) W33 A. The conversion to optical depth for L1551 IRS 5 was made using the continuum shown in Fig. 1. The spectra of W33 A and NGC 7538 IRS 9 are adapted from Lacy et al. (1984).

TABLE 1  
OPTICAL DEPTHS OF ICES AND DUST TOWARD XCN SOURCES

Molecule	Band Center ( $\text{cm}^{-1}$ )	L1551 IRS 5	W33A	NGC 7538 IRS 9
XCN	2165	0.16 <sup>a</sup>	1.30 <sup>b</sup>	0.20 <sup>b</sup>
CO	2140	0.80 <sup>c</sup>	1.20 <sup>c</sup>	2.60 <sup>c</sup>
CO	2135	0.16 <sup>c</sup>	0.43 <sup>c</sup>	0.43 <sup>c</sup>
H <sub>2</sub> O	3275	2.10 <sup>d</sup>	> 5.40 <sup>e</sup>	3.28 <sup>e</sup>
H <sub>2</sub> O	1670	...	1.75 <sup>e</sup>	0.45 <sup>e</sup>
CH <sub>3</sub> OH	1450	...	1.49 <sup>e</sup>	0.36 <sup>e</sup>
SiO <sub>x</sub>	1030	1.4 <sup>f</sup>	7.84 <sup>e</sup>	4.46 <sup>e</sup>

NOTES.—(a) this paper; (b) Lacy et al. 1984; (c) Tielens et al. 1991; (d) Sato et al. 1990; (e) Willner et al. 1982; (f) Willner et al. 1982; (f) Cohen & Schwartz 1983.

ice absorption features in the spectra of embedded objects such as W33 A and NGC 7538 IRS 9. The CO and NH<sub>3</sub> concentrations are enhanced by a factor of 2–5 relative to the normal interstellar ice abundance to increase the XCN yield and thereby facilitate its study. It is important to study the band carrier in a realistic ice as matrix effects can produce significant spectral variations. A full description of the experimental procedure and equipment used to obtain this laboratory data can be found elsewhere (Allamandola et al. 1988).

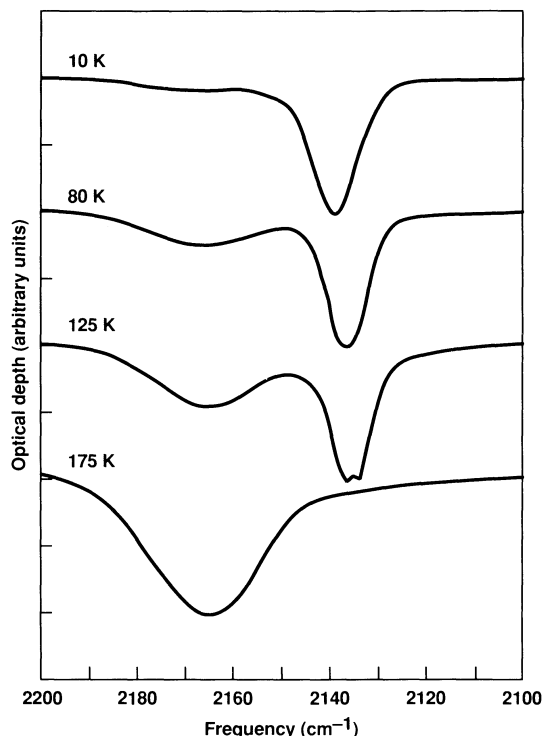


FIG. 3.—Optical depth spectra over the 2200–2100  $\text{cm}^{-1}$  wavenumber interval of a photolyzed interstellar ice analog. The original  $\text{H}_2\text{O}:\text{CH}_3\text{OH}:\text{CO}:\text{NH}_3 = 100:50:10:10$  ice was deposited at 10 K with simultaneous photolysis for 15 hr. The ice was then warmed to the listed temperatures and spectra were taken. Note that all the spectra have been normalized to have the same maximum optical depth in the deepest band.

The top spectrum in Figure 3 was taken from the sample after it was deposited at 10 K with simultaneous ultraviolet irradiation for 15 hr. Although the XCN feature is clearly present in this spectrum, the 2200–2100  $\text{cm}^{-1}$  wavenumber interval is dominated by frozen CO absorption. Note that the CO feature peaks at 2139  $\text{cm}^{-1}$  in this photolyzed ice, not at the 2135  $\text{cm}^{-1}$  position typical of an unirradiated sample (Sandford et al. 1988).

After irradiation, the sample was warmed in 10 K steps at a rate of 2 K per minute. A spectrum was taken at each temperature after the ice had been allowed to equilibrate for 10 minutes. There is not much change in the relative strengths of the CO and XCN bands until about 80 K (second spectrum in Fig. 3) at which time some of the CO begins to escape from the ice. During this period the CO band position moves to about 2137  $\text{cm}^{-1}$ , closer to the 2135  $\text{cm}^{-1}$  value typical for CO in an  $\text{H}_2\text{O}$ -rich ice (Sandford et al. 1988). This shift occurs gradually, starting between 50 and 60 K. Note that the apparent increase in the depth of the XCN band with respect to that of CO is due to the sublimation of CO, and not an increase in the amount of XCN. This general trend continues as the sample is warmed to higher temperatures. The third spectrum is that of the ice at 125 K, at which point the solid CO feature splits into two components, one due to CO still in an amorphous  $\text{H}_2\text{O}$  lattice, the other presumably due to CO trapped in the  $\text{H}_2\text{O}-\text{CH}_3\text{OH}$  type II clathrate which spontaneously forms near this temperature under vacuum (Blake et al. 1991). Finally, at about 150 K all of the remaining CO is lost when the  $\text{H}_2\text{O}$  ice matrix

sublimes (Sandford & Allamandola 1988, 1990). The remaining material consists of a “refractory” organic residue that is described in detail in Allamandola et al. (1988). The carrier of the XCN band remains in the residue until a temperature of 200 K is reached, at which time it begins to sublime. The last of the XCN usually leaves the substrate by the time the temperature reaches  $\sim 250$  K.

Note that the position of the XCN band varies only slightly over the entire temperature range. At 10 K the band peak is at 2168.4  $\text{cm}^{-1}$  and steadily shifts to 2166.3  $\text{cm}^{-1}$  at 100 K. At 150 K the band peak is at 2162.2  $\text{cm}^{-1}$  when the ice has converted to cubic  $\text{H}_2\text{O}$  ice. Finally, after the ice sublimates, the XCN band peak is at 2164.0  $\text{cm}^{-1}$  in the refractory residue. This modest variation in the frequency of the band peak is in contrast to the temperature-dependent behavior observed in the laboratory studies reported in Lacy et al. (1984), where a good fit with the astronomical data was obtained only when all the volatiles had evaporated. This difference presumably arises from the fact that the composition of the ice studied in Lacy et al.,  $\text{CO}:\text{NH}_3 = 3:1$ , is quite different from the more realistic interstellar ice reported here. The earlier sample composition was chosen principally to demonstrate the dependence of the XCN feature on the presence of carbon and nitrogen atoms in the ice in order to make the assignment, not to mimic an interstellar ice. The results shown in Figure 3 show that the absorption feature produced by the laboratory XCN carrier is relatively insensitive to its molecular environment in a realistic ice. The signal-to-noise ratios in both the L1551 IRS 5 and NGC 7538 IRS 9 data are insufficient for determining the interstellar XCN band peak position accurately enough to measure these temperature-modulated variations; however, the XCN band appears to peak in the wavenumber interval 2165–2162  $\text{cm}^{-1}$  in the W33 A spectrum. These three astronomical spectra suggest possible variations in the XCN band center may be detected by current generation spectrometers (with resolving powers greater than 500) in data with improved signal to noise ratios. However, the telluric window is too narrow to define the true baseline and this produces an additional uncertainty in the peak frequency.

### 3.3. The XCN Feature

In Figure 4, we compare the XCN band in the spectra of W33 A, NGC 7538 IRS 9, L1551 IRS 5, and the 10 K irradiated laboratory sample warmed to 60, 125, and 175 K. All the spectra in this figure have been scaled to have the same optical depth in the center of the XCN band. This figure demonstrates that the profile and position of the interstellar XCN band are essentially the same in all three astronomical objects, and that the feature is well reproduced by the laboratory spectra. *Temperature cycling is not necessary to shift the laboratory band to match the interstellar band as was the case in the earlier study reported by Lacy et al. (1984) on the simpler  $\text{CO}:\text{NH}_3$  ice.* Thus, there is no need for the scenarios that invoke warming by local infrared sources or long time scales in cooler regions considered by Lacy et al.; however, the questions of production efficiencies and production sites discussed by Lacy et al. remain valid.

## 4. DISCUSSION

The column density of an absorbing species ( $N_x$ ) is given by the formula

$$N_x \approx \frac{\Delta v_x \tau_x}{A_x}, \quad (1)$$

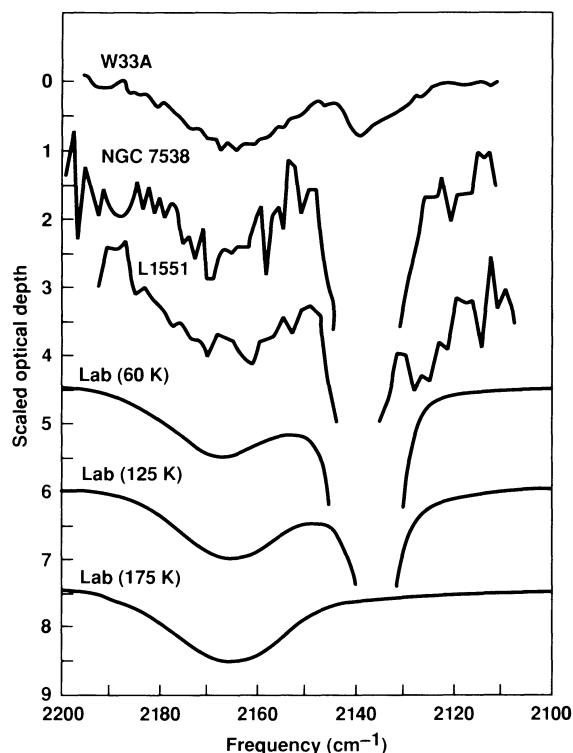


FIG. 4.—Comparison of the 2200–2100  $\text{cm}^{-1}$  optical depth spectra of W33 A, NGC 7538 IRS 9, L1551 IRS 5, and the laboratory ice analogs photolyzed and warmed to 60, 125, and 175 K. To facilitate comparison, all the spectra have been normalized to have the same optical depth at the center of the XCN band. As discussed in the text the three high points between 2193 and 2185  $\text{cm}^{-1}$  in the spectrum of L1551 IRS 5 are due to absorption in the bright star spectrum.

where  $x$  is the molecular band under consideration,  $\Delta\nu_x$  is the full width at half-maximum of the band,  $\tau_x$  is the optical depth at band center, and  $A_x$  is the integrated absorbance ( $A$ -value) of the band. From the L1551 IRS 5 absorbance spectrum in Figure 2a we have determined that  $\tau_x$  at 2140 (CO frozen in a nonpolar matrix) and 2135  $\text{cm}^{-1}$  (CO frozen in a polar matrix) have values of 0.90 and 0.40, respectively, and  $\tau_x$  at 2165  $\text{cm}^{-1}$  (XCN) has the value 0.16. Our values for CO are in agreement with those reported by Tielens et al. 1991 (see Table 1). Since the frozen CO observations obtained by Tielens et al. have a higher signal-to-noise ratio than our frozen CO observations, we use the Tielens et al. values for CO optical depths in our

analysis. The column densities toward L1551 IRS 5 are given, along with appropriate values for  $\Delta\nu$  and  $A$ , in Table 2. The column density of XCN is comparable to that of frozen CO in both the nonpolar and polar ices while the column density of frozen  $\text{H}_2\text{O}$  is an order of magnitude larger than the combined column densities of XCN and frozen CO. From Table 2 we see CO frozen in a nonpolar ice is  $\sim 3$  times more abundant than CO frozen in a polar ice. The relative abundance of the total column density of frozen CO to frozen  $\text{H}_2\text{O}$  is  $N_{\text{CO}(\text{total})}/N_{\text{H}_2\text{O}} \approx 0.09$ , although the ratio of frozen CO to frozen  $\text{H}_2\text{O}$  in the polar matrix, where the CO is less abundant, is  $N_{\text{CO}(\text{polar})}/N_{\text{H}_2\text{O}} \approx 0.02$ . The relative abundance of XCN to frozen  $\text{H}_2\text{O}$  is  $0.02 \leq N_{\text{XCN}}/N_{\text{H}_2\text{O}} \leq 0.05$ . These ice abundance ratios, derived from the astronomical data alone, are consistent with the composition of the starting ice used in the laboratory experiments.

With the 2.7 aperture of CGAS, we do not have sufficient angular resolution to uniquely constrain the location of the absorbing ices. The results of other studies (Stoekel et al. 1988), however, suggest that the visual optical depth through material in the immediate circumstellar environment of L1551 IRS 5, and along the direct line of sight to L1551 IRS 5 ( $A_v \geq 19$  mag), is much greater than the visual optical depth through material in the immediate circumstellar environment of L1551 IRS 5, but not along the line of sight to the central source ( $A_v \approx 0$ ). Thus it appears this ice-rich column is not representative of a grain population distributed in a spherically symmetric cloud around the central core. We conclude that most of these ices may lie in the circumstellar disk oriented nearly edge-on to our line of sight.

The laboratory ice experiments show that neither the CO nor the  $\text{H}_2\text{O}$  ices remain stable above  $\sim 150$  K while the more refractory XCN remains solid only below  $\sim 250$  K. These ices therefore could not exist in the inner region of the disk, closer than 5–10 AU from the protostellar photosphere of L1551 IRS 5. They could exist in regions of this disk that are comparable in temperature to the outer planet region of our solar system, where comets in the Sun's Oort cloud are thought to have formed.

## 5. CONCLUSIONS

We have measured a broad and shallow absorption band at 2165  $\text{cm}^{-1}$  in the spectrum of L1551 IRS 5 that we interpret as produced by XCN in a circumstellar disk around this source. Thus, there are now three extra-solar system sources, two embedded sources and an FU Orionis object, for which this feature has been detected. This XCN feature is similar in all three of these objects and can be well fitted with spectra obtained by photolyzing an ice of reasonable interstellar com-

TABLE 2  
COLUMN DENSITIES OF ICES TOWARD L1551 IRS 5

Molecule	Band Width <sup>a</sup> $\Delta\nu$ ( $\text{cm}^{-1}$ )	Absorbance $A$ ( $\text{cm molecule}^{-1}$ )	Column Density $N$ ( $\text{molecules cm}^{-2}$ )	Column Mass $m$ ( $\text{g cm}^{-2}$ )
XCN .....	20	$2\text{--}4 \times 10^{-17}$	$0.8\text{--}1.6 \times 10^{17}$	$>3.5 \times 10^{-6}$
CO (2140 $\text{cm}^{-1}$ ) .....	6	$2.0 \times 10^{-17}$	$2.4 \times 10^{17}$	$1.1 \times 10^{-5}$
CO (2135 $\text{cm}^{-1}$ ) .....	10	$2.0 \times 10^{-17}$	$0.8 \times 10^{17}$	$3.7 \times 10^{-6}$
$\text{H}_2\text{O}$ .....	335	$2.0 \times 10^{-16}$	$3.5 \times 10^{18}$	$1.1 \times 10^{-4}$

<sup>a</sup> Band width ( $\Delta\nu$ ) and absorbance ( $A$ ) values for XCN from d'Hendecourt & Allamandola (1986); for CO from Sandford et al. (1988); for  $\text{H}_2\text{O}$  from d'Hendecourt & Allamandola (1988).

position. The fit is temperature insensitive up to  $\sim 250$  K, so the XCN-containing material could exist in the ice phase or reside in warmer organic residues. With spectra from only three objects, we are unable to determine whether the XCN around L1551 IRS 5 has been preserved in a dense disk from the protostellar cloud or whether intense particle and high-energy photon flux from the FU Orionis star has stimulated production of these ices in the disk.

We confirm the existence of a narrow absorption band at  $2140\text{ cm}^{-1}$  ( $4.67\text{ }\mu\text{m}$ ) produced by frozen CO trapped in a nonpolar matrix and a broader, weaker absorption band at

$2135\text{ cm}^{-1}$  ( $4.68\text{ }\mu\text{m}$ ) produced by CO frozen in a polar matrix (probably  $\text{H}_2\text{O}$ ). Frozen  $\text{H}_2\text{O}$  is approximately 10 times more abundant than frozen CO and 20 times more abundant than XCN.

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