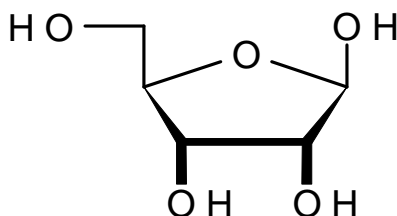
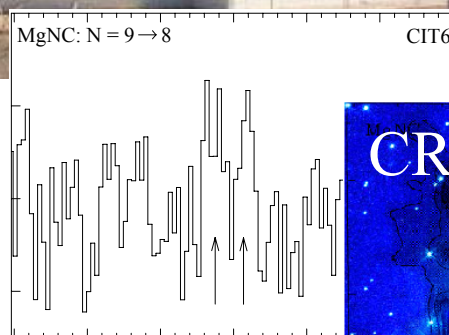
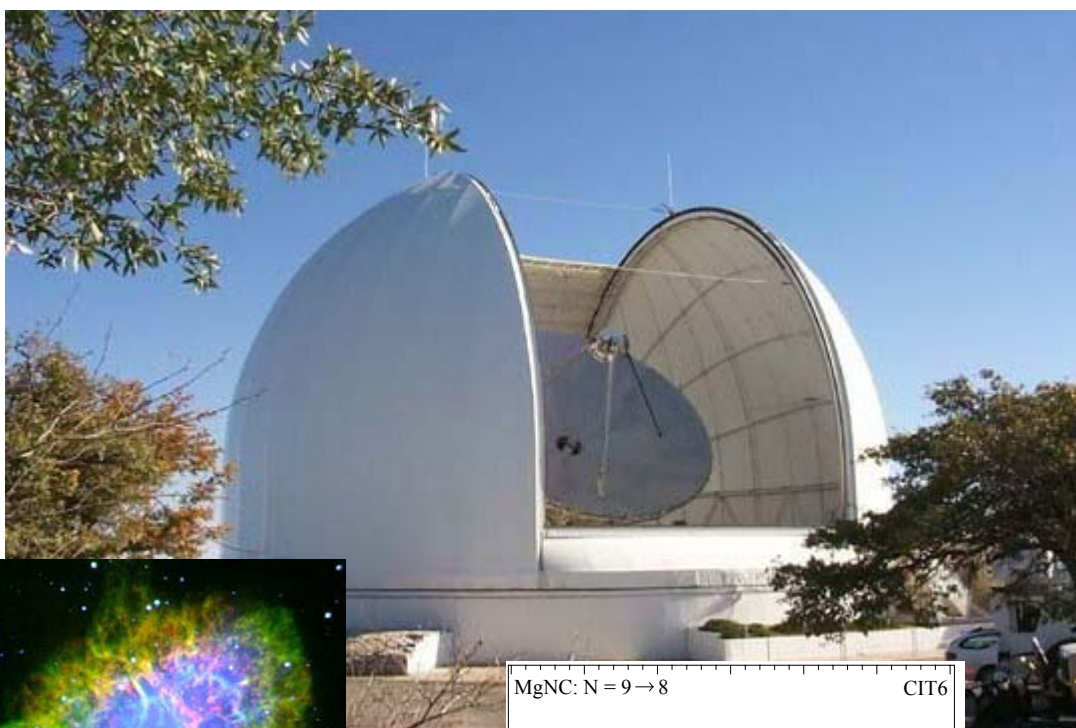


Interstellar Molecules as Probes of Prebiotic Chemistry: A Laboratory in Radio Astronomy

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I. Introduction

i) *Interstellar Molecules: An Overview*

The discovery of interstellar molecules and the establishment of the field of astrochemistry began in the early 1970's with the discovery of carbon monoxide (CO) in the Orion Nebula (ref. Penzias, Wilson and Jefferts 1970). At the time it was thought that the interstellar medium, i.e. the gas and material between the stars, was primarily atomic in nature, and that this environment was too harsh for anything more complicated than a few simple diatomics to exist. The discovery of CO, which was quickly followed by the observation of NH₃, H₂CO, HCN, H₂S, SO₂ and various other species throughout the 1970's and 1980's, changed this picture of interstellar space dramatically. It is now thought that 50% of the material in the inner 10 kpc of the Milky Way Galaxy is molecular in nature, and the current lists of known, gas-phase, interstellar chemical compounds is over 120 (see Table 1), not including isotopic variants. Much molecular material also exists in external galaxies, as well. We can now truly talk about a "molecular universe."

Table 1. Known Interstellar Molecules

2	3	4	5	6	7	8	9	10		
H ₂	CH ⁺	H ₂ O	C ₃	NH ₃	SiH ₄	CH ₃ OH	CH ₃ CHO	CH ₃ CO ₂ H	CH ₃ CH ₂ OH	CH ₃ COCH ₃
OH	CN	H ₂ S	MgNC	H ₃ O ⁺	CH ₄	NH ₂ CHO	CH ₃ NH ₂	HCO ₂ CH ₃	(CH ₃) ₂ O	CH ₃ (C≡C) ₂ CN
SO	CO	SO ₂	NaCN	H ₂ CO	CHOOH	CH ₃ CN	CH ₃ CCH	CH ₃ C ₂ CN	CH ₃ CH ₂ CN	(CH ₂ OH) ₂
SO ⁺	CS	NNH ⁺	CH ₂	H ₂ CS	HC≡CCN	CH ₃ CN	CH ₂ CHCN	C ₇ H	H(C≡C) ₃ CN	
SiO	C ₂	HNO	MgCN	HNCO	CH ₂ NH	CH ₃ SH	H(C≡C) ₂ CN	H ₂ C ₆	H(C≡C) ₂ CH ₃	
SiS	SiC	SiH ₂	HOC ⁺	HNCS	NH ₂ CN	C ₅ H	C ₆ H	CH ₂ OHCHO	C ₈ H	11
NO	CP	NH ₂	HCN	CCCN	H ₂ CCO	HC ₂ CHO	c-CH ₂ OCH ₂	HC ₆ H		H(C≡C) ₄ CN
NS	CO ⁺	H ₃ ⁺	HNC	HCO ₂ ⁺	C ₄ H	CH ₂ =CH ₂	H ₂ CC(OH)H			
HCl	HF	NNO	AINC	CCCH	c-C ₃ H ₂	H ₂ C ₄				12
NaCl	SH	HCO	SiCN	c-C ₃ H	CH ₂ CN	HC ₃ NH ⁺				C ₆ H ₆
KCl	HD	HCO ⁺	SiNC	CCCO	C ₅	C ₅ N				
AlCl	FeO?	OCS	H ₂ D ⁺	C ₃ S	SiC ₄	C ₅ S?				13
AlF		CCH	NH ₂	HCCH	H ₂ C ₃					H(C≡C) ₅ CN
PN		HCS ⁺	KCN?	HCNH ⁺	HCCNC					
SiN		c-SiCC	SiH ₂ ?	HCCN	HNCCC					
NH		CCO		H ₂ CN	H ₂ COH ⁺					
CH		CCS		c-SiC ₃						
				CH ₂ D ⁺ ?						

The chemical species listed in Table 1 illustrate the complexity and "non-terrestrial" nature of interstellar chemistry. About 50% of the compounds found in the interstellar medium, or "ISM," are species that are not stable under normal lab conditions, namely free radicals and molecular ions. These species would be more common as reaction intermediates in terrestrial chemistry. On the other hand, many of these molecules are compounds typically found in abundance on earth: H₂O, CH₃OH, CH₃CH₂OH, (CH₃)₂O, and so forth. Even acetone has been found, and after some debate, a simple sugar, glycolaldehyde. The presence of several "natural products" in interstellar space with common organic functional groups naturally leads one to speculate, how complex is interstellar chemistry? Can true "biogenic" compounds be formed in the far reaches of interstellar space, and if so, would these chemicals play a role in the generation of simple biological functions?

ii) *Molecular Clouds and Gas Envelopes around Old Stars: Interstellar Flasks*

Perhaps these questions could be better answered by considering where these gas-phase molecules exist in space and under what physical conditions. In our galaxy, as well as external galaxies, molecules are present in two types of objects: 1) so called “molecular” or dense clouds, and 2) in gaseous envelopes that exist around old stars, known as asymptotic giant branch stars, or “AGB” stars, as a result of mass loss from the star in the later phases of helium-burning. As one might expect, these objects have similar physical conditions. By terrestrial standards, they are typically cold. Molecular clouds usually have gas kinetic temperatures in the range $T_k \sim 10\text{--}50\text{ K}$, but in rare, small, confined regions towards young stars, T_k can be greater than 1000 K

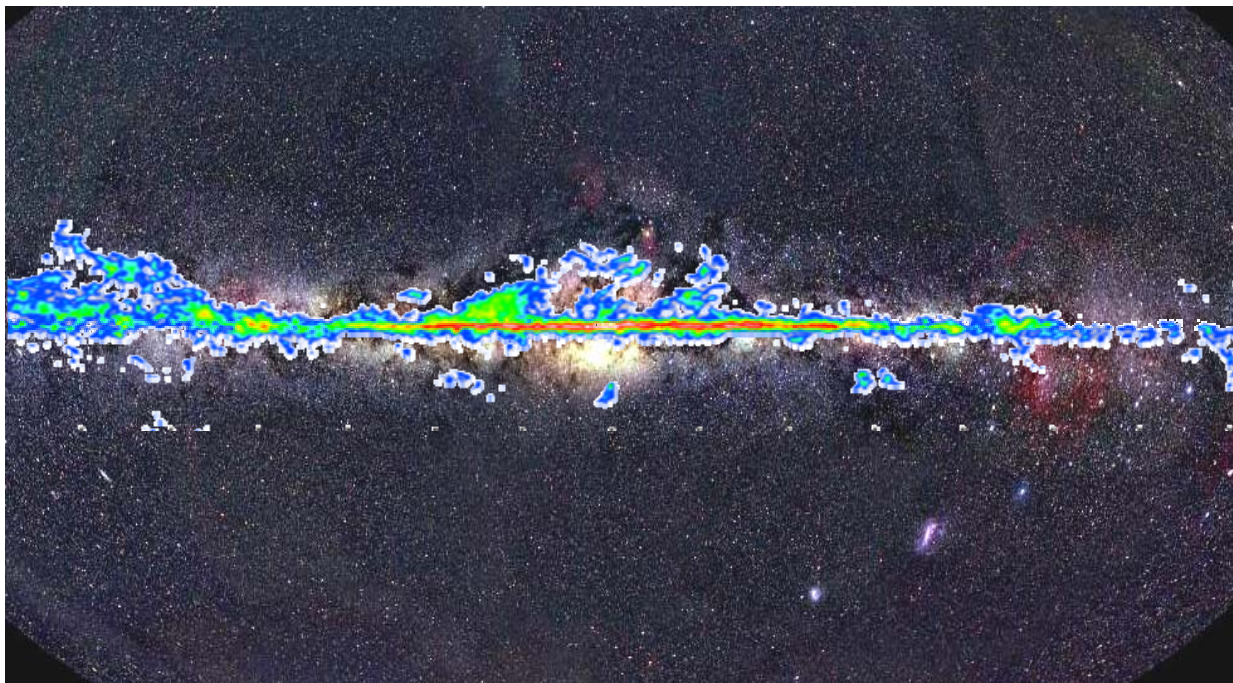


Figure 1: The distribution of molecular clouds in our galaxy, as traced in emission of carbon monoxide at 115 GHz (CO: $J = 1 \rightarrow 0$ transition).

Stellar envelopes, known as “circumstellar envelopes” or “CSE’s”, have similar temperatures in the outer part, but they increase significantly to as high as $\sim 1000\text{ K}$ at the inner shell near the star. These regions are also important sources of interstellar dust, which condenses out of hot gas leaving the stellar surface, or photosphere.

Densities of molecular clouds fall in the range $10^3\text{--}10^6$ particles per cc or (cm^{-3}), corresponding to pressures of $10^{-15}\text{--}10^{-12}$ torr at 10 K. Hence, while these objects are “dense” by interstellar standards, they are ultra high vacuum in comparison with the terrestrial environment. For CSE’s there is a density gradient, with $n \sim 10^{10}$ particles per cc (cm^{-3}) close to the star in the inner shell, falling to $\sim 10^5$ (cm^{-3}) at the outer edges of the envelope.

Both molecular clouds and CSE’s play important roles in astrochemistry and astrobiology. Many of these clouds eventually collapse into stars and solar systems. Our own solar system began, for example, as a molecular cloud. Many of these clouds are also very massive – up to 10^6 solar masses, and hence contain a tremendous amount of material, mostly in molecular form. The amount of molecular material in a given cloud fall outweighs that found on both.

Circumstellar envelopes are important because they are a source of heavy elements to the interstellar medium: carbon, oxygen, magnesium, phosphorus, and so forth.

iii) *Radio Astronomy: “NMR” on the Universe*

The study of astrochemistry relies on detecting a wide variety of chemical species and evaluating their abundances. Despite the fact that signals from molecules may be coming from thousands of light years away, a quantitative analysis can be performed on interstellar gas mixtures through the use of radio telescopes and remote sensing. Radio telescopes at first glance may seem an odd tool for a chemist, but these instruments exploit fundamental principles of molecular spectroscopy in a similar manner to a laboratory spectrometer.

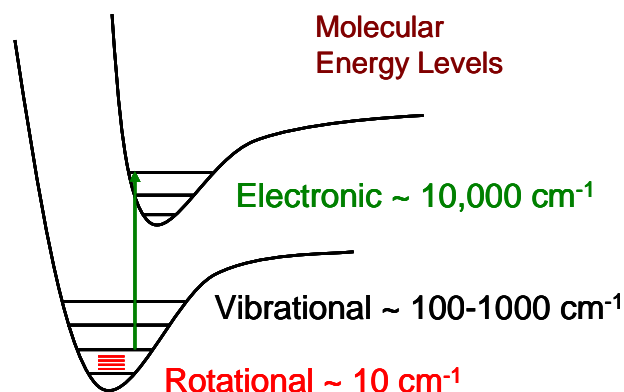


Figure 2: Energy levels of a diatomic molecule. The potential wells are individual electronic states. Within each of these “wells” lie vibrational and rotational levels.

To understand this statement, a quick review of physical chemistry is required. According to the Born-Oppenheimer approximation, molecules have rotational, vibrational, and electronic energy levels, as shown in Figure 2.

The electronic energy levels, shown here for a diatomic species, depend on the internuclear distance and hence are represented by potential wells. Within each well are the vibrational levels, which arise from the vibration of chemical bonds, as well as rotational levels, produced by end-over-end physical rotation of the nuclei. The electronic energy levels require an electron to change molecular orbitals; hence, correspond to the highest energy differences, found in the optical and ultraviolet regions of the electromagnetic spectrum. Molecular vibration corresponds to energies in the infrared region, while the differences in rotational energy levels are in the millimeter and sub-millimeter radio regimes around 1-10 cm⁻¹ or 30-300 GHz (1.4 - 14 K).

Given typical interstellar temperatures of 10-50 K, it is clear that only rotational energy levels of a given molecule will be populated. Collisions with other molecules populate the levels, and then they spontaneously decay to lower energy levels, resulting in the emission of photons at a frequency or wavelength corresponding to the energy difference between two levels. The energies of the rotational levels, and hence energy differences, depend exclusively on the masses of the atoms forming the molecule, the bond lengths, and the molecular geometries, i.e. the “moments of inertia” of a given chemical species. Because rotational motion means that nuclei must move, a diatomic molecule has two axes it can physically rotate around, as shown in Figure 3. These axes correspond to moments of inertia, $I = \mu r^2$, where r is the distance between the nuclei (or bond length) and μ is the reduced mass $= m_a m_b / (m_a + m_b)$, for a diatomic molecule of mass a and mass b . These moments of inertia, called I_b and I_c , are equivalent i.e. $I_b = I_c = I$. This moment of inertia defines the spacing of rotational energy levels of a molecule, and is related to the “so-called” rotational constant, B , where $B = h / (8\pi I)$.

Rotational energy levels are quantized, and we label them with a quantum number called J . The

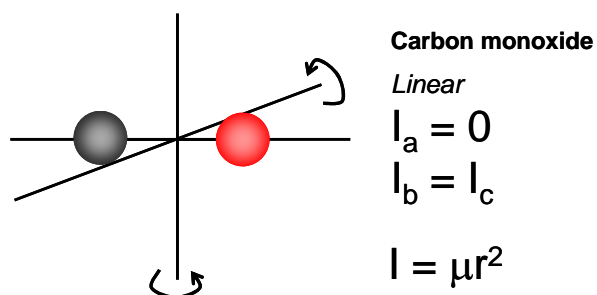


Figure 3: A diatomic molecule, its two equivalent rotational axes and corresponding moment of inertia, related to the rotational constant B .

approximate energies of the rotational levels are:

$$E_{\text{rot}} = BJ(J+1) \quad (1),$$

where $J = 0, 1, 2, 3$, etc. The frequencies of the photons correspond to the energy level differences, which follow the quantum selection rule $\Delta J = \pm 1$;

$$\nu = 2B(J+1) \quad (2).$$

The concepts are described in more detail in the laboratory exercise.

While the cold nature of the interstellar medium results in “high-resolution” spectra, i.e. spectral lines whose frequencies can be determined to one part in 10^7 , it also means that small corrections such as centrifugal distortion are absolutely necessary to identify interstellar species.

II. Radio Telescopes: A Hitchhikers Guide

Radio telescopes and their detector systems are very complicated instruments, and describing them in detail is not possible here. Nevertheless, some basic principles can be understood.

A radio telescope is basically a large satellite dish with an extremely smooth surface. The telescope diameter D and the observing wavelength λ establish the solid angle it subtends on the sky, i.e. beam size $\Theta_b \cong 1.2\lambda/D$. As shown in Figure 4, the signal from the sky coming from the direction that the telescope is pointed, is focused from the “primary dish,” to the “secondary” mirror or “sub-reflector,” which in turn directs the signal through an opening in the primary. The signal is then directed by mirrors into the appropriate detectors. At the ARO 12 m, there is a series of mirrors that do this task.

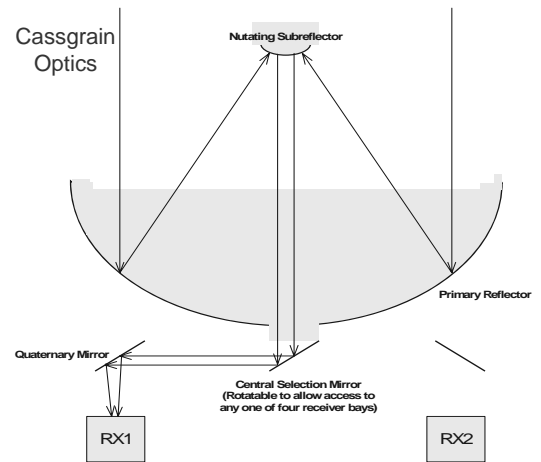


Figure 4: Basic optics of a radio telescope and a block diagram of the heterodyne detector system.

The complicated part of radio telescopes is the detector system. The signals coming in from interstellar space are very weak, and can only be detected with very “low noise” instruments. A low noise amplifier in principle could do the job, but these do not exist at millimeter and sub-millimeter wavelengths. Instead, a “superheterodyne” technique is used where the signal from the sky is “mixed” with a “local oscillator” in a device, appropriately labeled, the “mixer.” It is actually an SIS (superconductor-insulator-superconductor) diode placed in a waveguide cavity. When a low voltage is applied across the diode, it acts “non-linearly” and multiplies the signals together of all incoming waves. Mathematically, this “mixing” is equivalent to taking sums and differences of all incoming frequencies, to generate “intermediate frequencies” or $\nu_{\text{I.F.}}$. At a radio telescope, these intermediate frequencies are immediately sent to a low-noise amplifier, which can be built at such frequencies. The amplifier is constructed in such a way that only a certain range of frequencies can be amplified. At the 12 m, this frequency range is $\nu_{\text{I.F.}} = 1.5 \pm 0.5$ GHz.

The use of the mixer and amplifier combination thus determines what “sky” frequency is observed. To get the proper “difference frequency,” or intermediate frequency ($\nu_{\text{I.F.}}$), a local oscillator frequency ($\nu_{\text{L.O.}}$) is chosen. It then follows that the sky frequency observed will be:

$$\nu_{\text{sky}} = \nu_{\text{L.O.}} \pm \nu_{\text{I.F.}} \quad (5)$$

This equation implies that two sky frequencies are simultaneously observed, which is exactly the case. However, the mixers can be “tuned” to “reject” one set of frequencies. Typically, the so-

called “upper sideband” signals are observed, such that $\nu_{\text{sky}} = \nu_{\text{L.O.}} + \nu_{\text{I.F.}}$, or at the 12 m, $\nu_{\text{sky}} = \nu_{\text{L.O.}} + 1.5 \text{ GHz}$.

Once the signal is mixed down to the lower intermediate frequency, it is sent to a spectrometer “backend.” This device separates the signal as a function of frequency so that a spectrum can be obtained. Numerous spectral resolutions are available at the 12 M, depending on which backends are used. Because the I.F. amplifier works over a certain bandwidth, a range of frequencies ($\nu_{\text{sky}} \pm 0.5 \text{ GHz}$) is simultaneously detected at the mixer and subsequently can be fed into the spectrometer. This technique is called “multiplexing.” A complete spectrum is therefore obtained without having to “scan” the frequency source.

The local oscillator itself consists of an Indium phosphide chip that emits millimeter waves when a voltage is applied across it. It sits in a waveguide cavity, and the cavity size is adjusted with “backshorts” to induce the diode to oscillate at a specific frequency. This device is called a “Gunn oscillator,” because the chip employed is a “Gunn” diode. The Gunn oscillator has to be frequency stabilized because otherwise it would drift with time, causing the local oscillator and sky frequency to change also. The oscillation is stabilized using a “phase-lock loop,” which references the Gunn to a very stable frequency synthesizer, which in turn is referenced to a rubidium standard. This system stabilizes the Gunn frequency, and hence the sky frequency, to at least 1 part in 10^9 . The Gunn oscillator will have to be tuned and “phase-locked” before the observing can begin. This task is something the telescope operator will perform.

The signals that enter the backend then get sent to a computer disk. Data is collected, or “signal-averaged,” usually over a 6 minute time period. These 6 minute “scans” are recorded to the disk under a unique scan number. The data reduction computer is used to call up the scan number to view the data. Because the stability of the electronics is so good, a large number of scans can be signal-averaged to improve the signal-to-noise of the spectra.

The detectors at the 12 m telescope, called by the general term “receivers,” are dual polarization. This term means that signals are simultaneously collected by two mixers with orthogonal polarizations. There are two local oscillators for this purpose, one for each mixer. Because signals from interstellar space are randomly polarized, these two mixers collect independent signals that can be averaged to gain a factor of $\sqrt{2}$ in signal-to-noise. The noise level (T_{rms}) that can be achieved follows the radiometer equation:

$$T_{\text{rms}}(1\sigma) = \frac{\sqrt{2} T_{\text{sys}}}{\sqrt{B_W \cdot \tau}} \quad (6),$$

where B_W is the bandwidth (or spectral resolution) of the individual channels of the backend, τ is the integration time, and T_{sys} is the “system temperature,” a measure of the detector plus sky noise. As this equation shows, the intensity scale is given in temperature units. Temperature (in Kelvin) is used for the intensity scale because originally all receivers at radio telescopes were referenced to liquid nitrogen.

The “system temperature” can vary with time because sky conditions change with source elevation and weather. Typically, the system temperature is measured every scan or every other scan. The T_{sys} is determined by a “cal scan.” As you will notice at the telescope, signals recorded are actually voltages. The “cal scan” sets the voltage-to-temperature scale by recording the voltage of the system while looking at a “load” at ambient temperature, and then recording a voltage while observing blank sky, which exhibits a colder temperature. With two voltages and two temperatures, the scale is set. The voltage coming out of the entire detector system, while looking at the sky, is then converted to system temperature.

The $\sqrt{2}$ in the radiometer equation arises from the observing technique, called “position-switching.” To remove background and sky instabilities, the telescope records signals “on-source,” and then “off-source,” at approximately 15-second intervals. The off-source data are then subtracted from the on-source. Good spectral baselines are hopefully the end result.

Two other techniques are important at the telescope: “pointing” and “focusing.” Despite the fact that radio telescopes are very precise dishes, they still suffer from gravitational deformations, usually as a function of the elevation. “Pointing” on a known strong source such as a planet generates small, real-time corrections that are entered into the tracking program. The result is that the telescope is physically pointed at the coordinates in the sky that are commanded. “Focusing” simply consists of moving the sub-reflector slightly in and out to optimize its position for maximum signal strength. Both pointing and focusing will be done during this lab.

III. Lab Exercise

This lab will focus on measuring spectra of two different interstellar molecules towards the molecular cloud NGC7538. The molecules to be observed are HC_3N and HCO^+ ; these are the same two species studied in the lab exercise.

HC_3N : Here three rotational transitions ($J = 10 - 9$, $J = 11 - 10$, and $J = 12 - 11$) will be observed over the 2 and 3 mm wavelength range (65 to 180 GHz). The frequencies of observation will be calculated by the observer as a pre-lab exercise. These observations will illustrate the precision of interstellar molecular spectroscopy, and then be used to construct a “rotational diagram” from which a molecule concentration, or “column density,” can be extracted, as well as the temperature of gas-phase HC_3N .

HCO^+ : Here the $J = 1 - 0$ and $J = 2 - 1$ transitions near 89 and 178 GHz will be observed (the $J = 2 - 1$ may be inaccessible if the weather is marginal). Frequencies for these transitions should be calculated as a prior exercise from the laboratory measurements.

Procedure for the HC_3N Observations:

The session will begin with observations of HC_3N . When you arrive at the telescope, you will give the operator the HC_3N frequencies you wish to observe. The operator may ask what source you are observing. The source and 1950.0 coordinates are:

$$\begin{aligned} \text{NGC7538} \quad \alpha &= 23^{\text{h}} 11^{\text{m}} 36^{\text{s}}.6 \\ \delta &= 61^{\circ} 11' 47''.0 \end{aligned}$$

$$V_{\text{LSR}} = -56.0 \text{ km/s}$$

This source can be found in the LMZ.CAT catalog of sources at the telescope. The V_{LSR} is the Doppler correction for this source relative to Earth. It is called “velocity with respect to the Local Standard of Rest,” hence V_{LSR} . All sources have such a Doppler correction.

Once the receiver is tuned, you will have to get to a planet to point and focus. First, a pointing “five-point” needs to be done on the closest planet. The operator will move the telescope and measure five positions across the planet: approximately half-a-beam width north, south, east and west of the planet, plus center position. The data is automatically analyzed and appears on the “Datserve” terminal. The intensity of the planet will be plotted vs. the positions measured as well as pointing corrections in azimuth and elevation. These are the corrections you will need to “fine tune” the position of the telescope on the sky. The operator will put the new corrections into the telescope drive computer. A similar task is used to focus the telescope by varying the axial subreflector position.

Question 1: What are some factors that could change the telescope pointing and focus settings?

The computer will take the data and produce a plot of focus versus intensity. The curve will increase to a maximum and decrease. The peak of this curve is the optimal focus position. The computer will also do a fit and print out the optimal focus position.

Next are the spectral line measurements. Give the operator your source name and position from the catalog and he will put in the Doppler correction and steer the telescope to the source. You will have to tell the operator:

- 1) Observing procedure: position-switching; off position: 30' west in azimuth
- 2) Scan time: 6 minutes
- 3) Spectrometer Backend Set-up: Use filter banks: 1000/1000; series/series: MAC: 600_2k_2

The telescope will measure an off-position set in azimuth because you want to track the same piece of sky that your source moves through. The spectrometer set-up places each receiver channel into a 1 MHz filter bank (256 ch. each) and splits the MAC in half for each channel. For more detail, see the ARO website: <http://aro.as.arizona.edu>.

The operator will start with a calibration scan to establish the system temperature, T_{sys} and hence temperature scale, then conduct the spectral line scan. A quick glimpse of the newly recorded data will appear on the computer terminal. We will “reduce” the data further using the UNIPOPS commands that appear in the Appendix.

Question 2: Do you have sufficient signal-to-noise to see the HC₃N line?

Question 3: Do you have sufficient signal-to-noise to accurately measure the line shape?

Question 4: If not, what can you do to increase the signal-to-noise ratio?

When one transition has been successfully measured, continue with the next one. The operator will have to retune for each frequency. Take at least one scan per frequency, for at least three transitions. Make a hardcopy of each spectrum for analysis. Removing a first order baseline from your final spectrum would be useful. You may also fit a Gaussian profile to each spectrum to determine the intensity and line width.

Procedure for the HCO[±] Observations: Ask the operator to tune to your first line of HCO⁺ near 89 GHz. Take enough scans to achieve high enough signal-to-noise to measure the line shape (height, width and center). Then try the 179 GHz line if weather permits.

Question 5: What factors affect the system noise of the telescope?

Question 6: What is the dominating noise factor at 179 GHz?

From your recorded spectra, measure the line parameters (height, width and center).

Compare the line centers (positions) with your predicted frequencies.

Question 7: Do the measured frequencies match your predicted frequencies?

Question 8: What are the possible sources of error?

IV. Analysis

HC₃N: You will use your HC₃N data to construct a “rotational diagram” from which you will determine an abundance, or “column density” of HC₃N (N_{tot}), and temperature characteristic of the molecule, called a “rotational” temperature, T_{rot} . For each transition observed, measure the peak intensity, T_L , in K, and the full-width-half-maximum (FWHM) line width, $\Delta V_{1/2}$, in km/s. These quantities are a measure of the amount of HC₃N present per rotational level. You will use these data in a fit to the following formula:

$$\log\left(\frac{3kT_L V_{1/2}}{8\pi^3 \nu S_{ij} \mu_0}\right) = \log\left(\frac{N_{\text{tot}}}{\zeta_{\text{rot}}}\right) - E_u \left(\frac{\log e}{T_{\text{rot}}}\right) \quad (7).$$

Here ν is the frequency of the transition, S_{ij} is the intrinsic quantum mechanical line strength, μ_0 the permanent electric dipole moment of the molecule, T_{rot} the rotational partition function, and E_u the energy of the upper level for a transition $J + 1 \rightarrow J$. For a linear molecule, $S_{ij} = J + 1$, and $\mu_0 = 3.724$ D for HC₃N. The partition function can be approximated as $\zeta_{\text{rot}} \sim T_{\text{rot}}/B$, and E_u must be calculated from Equation 1.

You will need to plot the left side of equation (Y) versus E_u (K). You should get approximately a straight line with a negative slope. From the slope, which equals $-\log e/T_{\text{rot}}$, calculate the rotational temperature. The Y-intercept is $\log(N_{\text{tot}}/\zeta_{\text{rot}})$. From this value, find N_{tot} .

HCO[±]: Compare the HCO⁺ line parameters with those of HCCCN.

Question 9: Which of the two molecules do you think is more abundant?

Question 10: Do the two molecules appear to be coming from the same source (hint: compare the center positions of the lines in units of velocity)?

Question 11: What other factors besides abundance do you think affect the observed line intensities?

APPENDIX: Simple commands for data reduction.

UNIPOPS is a data reduction program that was written for use with single dish radio telescope data. The program is capable of reducing most data taken with the KP12m telescope to its final format immediately at the telescope site. Spectral line telescope data is generally reduced to a Cartesian plot of frequency offset (MHz) vs. intensity (K). The frequency offset is relative to the rest frame of the molecule where all Doppler shifts have been accounted for in the operating software. In general, the data acquisition and reduction occurs as an interactive process of: (i) a calibration scan is taken, (ii) a short (about 6 minute) data scan is taken and written to the hard drive, (iii) the data is accumulated and averaged using a weighting function, (iv) a baseline is removed if necessary, and (v) steps (i) – (iv) are repeated until the desired signal to noise is achieved.

UNIPOPS is used to retrieve raw KP12m data from the disk and reduce each series of spectral line observations to a single Cartesian plot using a weighted average for each scan. UNIPOPS is able to do this in a number of ways, but we will stick to the absolute basics here. The data are written to the disk, each with its own unique scan number. There is a base scan number and a subscan number. The base scan number is listed sequentially for each observation made. The subscan number is listed as a decimal to the base number and corresponds to the different

backends used for the observation. There will be 4 subscan numbers for this exercise, e.g. 2.01, 2.03, 2.11 and 2.12 where the 01 and 02 subscans are the filterbanks and the 11 and 12 are the MAC.

A Quick Look at Each Scan

The first thing we will probably want to do is look at the raw data for each individual scan. This is done using the *get* command or the *f* and *s* macros in the following syntax:

```
LineF> get <scan>.<subscan> page show
LineF> <scan> f
LineF> <scan> s
```

To switch between the filterbanks and MAC use the following commands:

```
LineF> hcdata // changes the prompt to LineH> for MAC data
LineH> fbdata // changes the prompt to LineF> for filterbank data
```

The *get* command takes the scan denoted by *<scan>.<subscan>* and places it into the plotting array—NOTE when using *get hcdata* and *fbdata* are not needed. The commands *page* and *show* are added to actually plot the data to the screen. The macros *f* and *s* show the first and second filterbank or MAC channels on the screen with only a single command depending on the current prompt.

Averaging Two or More Scans Together

If you have two or more scans towards the same position on the sky, at the same frequency and same resolution, that data can be averaged together to improve the signal to noise. To do this is relatively easy as long as the scans are taken sequentially.

```
LineF> empty // make sure the accumulation array is empty
LineF> add(<scanlow>, <scanhigh>)
LineF> c1 // macro to average all of the first filterbank data together
LineF> c2 // macro to average all of the second filterbank data
LineF> cb // macro to average both the first and second filterbanks together
```

Removing a Baseline and Determining Line Parameters

Usually a polynomial baseline of order a few is needed to determine line parameter information. There are built in macros for each of these in the program:

```
LineF> nfit = <baseline order> // nfit is the order of the polynomial used in the fit
LineF> bset // will prompt you for mouse clicks in up to 16 regions
LineF> bshape bshow // optional commands to preview how the fit will look
LineF> baseline page show // removes the baseline and replots the spectrum
```

After a baseline is removed, Gaussian profiles are fit to each feature.

```
LineF> gset // will prompt you to select the left, center and right of the peaks
LineF> gshow // calculates the results and plots them on the screen.
```

If the fit does not converge, try setting the adverb *niter* = 1000 and run *gshow* again.

Printing and Exporting Data

To print any graphic shown on the screen use the command *gcopy* and to print the scan information, use the commands *header* *tcopy*.