I.   Observations

This homework exercise will focus on measuring molecular spectra towards four different interstellar sources: dark clouds, molecular clouds, AGB stars, and external galaxies. These observations will compare molecular features seen in dark vs. molecular clouds, demonstrate molecular line identification, examine isotope ratios and emission from masers and external galaxies.

Broad band spectrum: The region near 147.3 GHz will be observed towards the AGB star IRC+10216, the dark cloud L134N, and the molecular cloud W51M. The emission features seen in this bandpass represent typical data obtained from these types of sources.

CO: The $J = 1 \rightarrow 0$ transition of CO near 115 GHz will be observed towards L134N, W51M, the AGB star Chi Cyg, and the external galaxy M51. In addition, the $J = 1 \rightarrow 0$ transition of ^{13}CO near 110 GHz will be studied towards Chi Cyg. These observations will allow for kinematic information to be obtained for the four types of sources. The $^{12}C/^{13}C$ ratio will also be obtained for Chi Cyg.

SiO: The $v = 0$, $J = 2 \rightarrow 1$ and $v = 1$, $J = 2 \rightarrow 1$ transitions near 86 GHz will be observed in the star Chi Cyg. The spectra of the $v = 1$ transition will show maser emission. This transition is from the first excited vibrational state, which is ~1800 K above the ground state. Hence, without the maser action near the surface of the star, this transition would probably not be detectable.

Observing Procedure

        You will begin your observing session by logging into the telescope's observing computer remotely through the internet. This procedure will be demonstrated.

        Ask the telescope operator to tune to the frequency at 147.240 GHz. The operator will tune the local oscillator and radio receiver to this frequency. The operator may ask what source you are observing. The source and 1950.0 coordinates are:

$$IRC+10216 \ (V_{LSR} = -26.0 \text{ km/s}) \qquad \alpha = 9^h \ 45^m \ 14.8^s$$
$$\delta = 13^o \ 30' \ 40''$$

This source can be found in the XRC.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 or continuum source to point and focus. Ask the operator to go to Saturn. First, a pointing "five-point" needs to be done. The operator will move the telescope and measure five positions across the source: approximately

half-a-beam width north, south, east and west of the source, plus center position. One of the computers will fit these data points, all which appear on the "Dataserve" terminal. The intensity of the source, in Jy, will appear at the five positions measured, as well as pointing corrections in azimuth and elevation, see Figure 1. These are the corrections you will need to "fine tune" the position of the telescope on the sky. A few such pointing scans may have to be done to achieve a consistent set of pointing corrections. The operator will put the new corrections into the telescope drive computer.
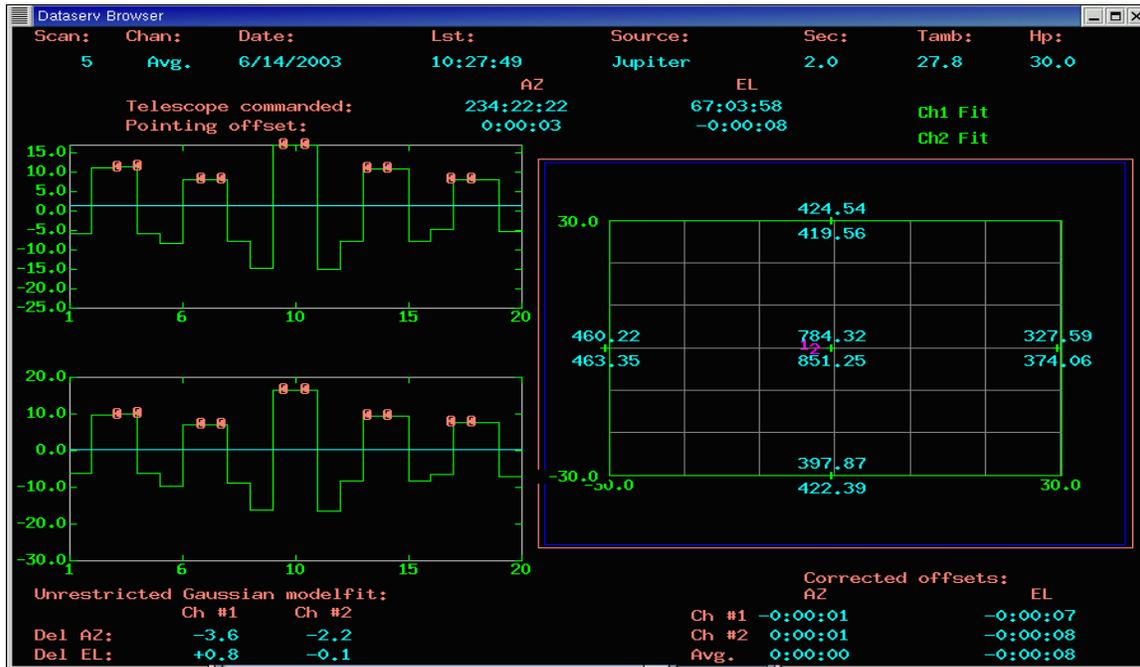

Figure 1: A pointing "5-point" scan displayed in "Dataserve."

The next task is to focus the telescope. The operator will move the subreflector to a series of different positions and measure the temperature of the source at each position. The computer will take the data and produce a plot of focus versus intensity. The curve will increase to a maximum and decrease, see Figure 2. The peak of this curve is the optimal focus position. The computer will also do a fit and print out the optimal focus position. You may have to iterate a few times with the focus.

Next are the spectral line measurements. Give the operator your source name and position from the catalog and he will steer the telescope to the source.

You will have to tell the operator:
1) <u>Observing procedure</u>: Beam-switching, offset +/- 2 arcminutes
2) <u>Scan time</u>: 6 minutes
3) <u>Spectrometer Backend Set-up</u>: Use filter banks: 1000/2000; parallel/parallel: MAC: 600_2k_2

The telescope will measure an off-position set in azimuth. The spectrometer set-up places each receiver channel into a 1000 kHz and 2000 kHz filter bank (2 by 128 channels each)

and splits the Millimeter AutoCorrelator (MAC) in half for each channel. The MAC is a 1.5 bit autocorrelating digitizer that can sample the telescope IF at a rate of 2 GHz. A digital waveform is generated by comparing adjacent samples of data and representing those that are increasing with time a 1, those that are decreasing with time a –1, and those that remain the same a 0. Bit resolution is dramatically improved by averaging in the time domain, e.g. Average (1+0) = 0.5, Average (1+1+0) = 0.7, etc. The frequency information is obtained by fast Fourier transform of
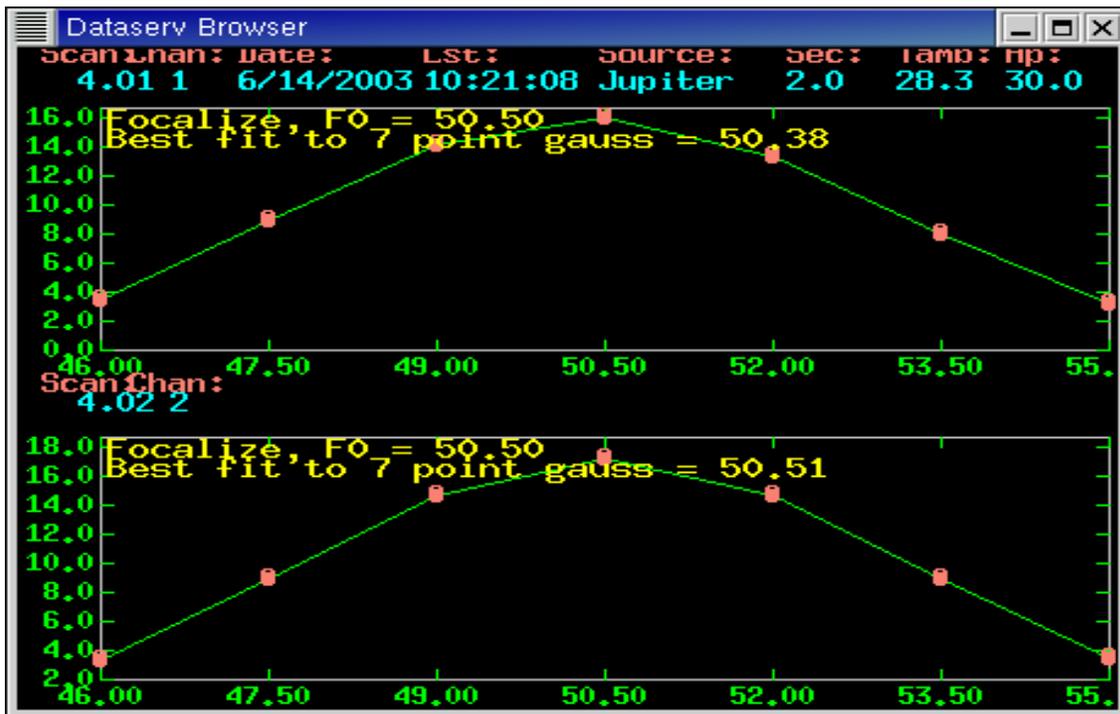

Figure 7: A "focus" scan which shows planet intensity as a function of focus positions.

the generated wave. For more detail, see the ARO website: http://aro.as.arizona.edu.

Once the spectrometers (also called "backends") are connected, the operator will start with a calibration scan to establish the T_{sys} and hence temperature scale, then take the first spectral line scan. When finished, it will be recorded under a scan number that the operator will log. Pull the scan up on the computer screen. You will have to "reduce" the data by averaging the two receiver channels (see Appendix II for commands). It is best that you first look at each channel and see if they agree, and then take the average. You will want to do this separately for the filter bank and MAC data (see Appendix II).

You will need to signal-average or integrate on this source for 2 scans to see data with a good signal-to-noise ratio. Once this is achieved, you will move to L134N. Take 4 scans on this source.

L134N (V_{LSR} = 2.5 km/s) $\alpha = 15^h\ 51^m\ 24.0^s$
                                    $\delta = -2^o\ 43'\ 31''$

1) Observing procedure: Position-switching, off position: 30 arcminutes west in azimuth

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2) <u>Scan time</u>: 6 minutes
3) <u>Spectrometer Backend Set-up</u>: Use filter banks: 1000/2000; parallel/parallel: MAC: 600_4k_2

Next move to W51M. Take 2 scans on this source and note the lines observed in each of the three sources.

W51M (V_{LSR} = 57.0 km/s) $\alpha = 19^h\,21^m\,26.2^s$
$\delta = 14^o\,24'\,43''$

1) <u>Observing procedure</u>: Position-switching, off position: 30 arcminutes west in azimuth
2) <u>Scan time</u>: 6 minutes
3) <u>Spectrometer Backend Set-up</u>: Use filter banks: 500/1000; parallel/parallel: MAC: 600_2k_2

<u>SiO Observations</u>

Next have the operator tune to the v = 0, J = 3 → 2 transition of SiO at 130.268702 GHz LSB. You will be observing the source Chi Cyg. Take two scans on the source.

Chi Cyg (V_{LSR} = 9.5 km/s) $\alpha = 19^h\,48^m\,38.5^s$
$\delta = 32^o\,47'\,10''$

You will use this setup for SiO:
1) <u>Observing procedure</u>: Beam-switching, offset +/- 2 arcminutes
2) <u>Scan time</u>: 6 minutes
3) <u>Spectrometer Backend Set-up</u>: Use filter banks: 250/500; parallel/parallel: MAC: 150_8k_2

Next have the operator tune to the v = 1, J = 3 → 2 transition of SiO at 129.363638 GHz LSB. Take two scans on the source. Note the intensity of the signals.

<u>CO Observations</u>

Have the operator tune to 110.20135 GHz for ^{13}CO. Take 6 scans towards Chi Cyg using the previous setup, and note the intensity. Next have the operator tune to 115.27120 GHz. Take 2 scans on this source. Note the intensities and line widths of the CO emission features.

Then take 2 scans on L134N with this setup:

1) <u>Observing procedure</u>: Position-switching, off position: 30 arcminutes west in azimuth
2) <u>Scan time</u>: 6 minutes
3) <u>Spectrometer Backend Set-up</u>: Use filter banks: 100/250; parallel/parallel: MAC: 150_8k_2

Next take 2 scans on W51M with this setup:

1) <u>Observing procedure</u>: Position-switching, off position: 30 arcminutes west in azimuth
2) <u>Scan time</u>: 6 minutes
3) <u>Spectrometer Backend Set-up</u>: Use filter banks: 500/1000; parallel/parallel: MAC: 600_2k_2

Next then move to M51 and take 4 scans on this galaxy with the following setup. Note the large V_{LSR} and line width

M51 (V_{LSR} = 470.0 km/s) $\qquad$ $\alpha = 13^h\ 27^m\ 46.3^s$

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ $\delta = 47^o\ 27'\ 10''$

1) <u>Observing procedure</u>: Position-switching, off position: 30 arcminutes west in azimuth
2) <u>Scan time</u>: 6 minutes
3) <u>Spectrometer Backend Set-up</u>: Use filter banks: 2000/2000; series/series: MAC: 600_2k_2

II.   Analysis

Please include all spectra with the homework that is handed in.

1. Broad band spectrum
a) From the spectra, identify the emission features observed towards the three sources. You can find spectral line lists at: http://physics.nist.gov/cgi-bin/micro/table5/start.pl, http://spec.jpl.nasa.gov/, and http://www.ph1.uni-koeln.de/vorhersagen/. Why are the lines different for the three sources?

b) For IRC+10216, explain the line profiles observed for the different molecules.

2. CO
a) Identify any other features in the CO spectrum.

b) From the line widths, estimate the gas kinetic temperature for the observed sources. Why is the line width larger for M51?

c) Calculate the $^{12}C/^{13}C$ ratio for Chi Cyg. Why might this value not be the true ratio in this source? How does this compare to the solar system value? What does this mean for star formation in the local solar neighborhood?

d) Determine the CO abundance in Chi Cyg, M51, W51M, and L134N.

4. SiO
a) Using the SiO spectra, calculate the vibrational temperature. Explain your result.

b) Given a kinetic temperature of 200 K and assuming the observed temperature of the $v = 0$ line of SiO, calculate the intensity of the $v = 1$, $J = 2 \rightarrow 1$ transition for both sources. Why does this differ from your observations?

<u>**APPENDIX I**</u>: Radio Telescopes and Receivers

A radio telescope is basically a large satellite dish with an extremely smooth surface. The Arizona Radio Observatory (ARO) dish is 12 meters in diameter with a surface accuracy to better than 0.1 mm. As shown in Figure 5, the signal from the sky is focused from the "primary reflector," 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. Any dish has a limited angular resolution or diffraction limit, meaning that it cannot distinguish two sources of radiation separated on the sky by less than a certain angle θ. A patch of sky whose diameter is ~θ is called the beam of a radio telescope, which determines how detailed a mapping it can do. For a telescope diameter D and the observing wavelength λ, the beam diameter is $\theta \cong 1.2\lambda/D$. For your observations, D = 12 m and λ = 3 mm, so $\theta \cong 0.0003$ radians = 62 arcseconds = about 1/30 of the diameter of the Moon = a US quarter seen at a distance of 80 meters = ~angular resolution of the human eye.

The signals from interstellar space are very weak and must be amplified while at the same time minimizing the inevitable addition of instrumental random noise to the signal. The "superheterodyne" technique is used where the signal from the sky is "mixed" (combined) with a "local oscillator" in a device called the "mixer." In this way, the sky signal (at a frequency ν_{sky}, say, of 88 GHz) is converted to a much lower frequency, called the "intermediate frequency" ν_{IF}, where it can be more conveniently and accurately handled. The mixer generates the intermediate frequency ν_{IF} by the sky signal with the local oscillator (at a frequency ν_{LO}), which is mathematically equivalent to producing sums and differences of all incoming frequencies. This intermediate frequency is then immediately sent to a low-noise amplifier constructed such that only a certain range of frequencies (a certain bandwidth) is amplified. For the ARO receivers, $\nu_{IF} = 1.5$ GHz with a bandwidth of 1.0 GHz centered on that frequency.
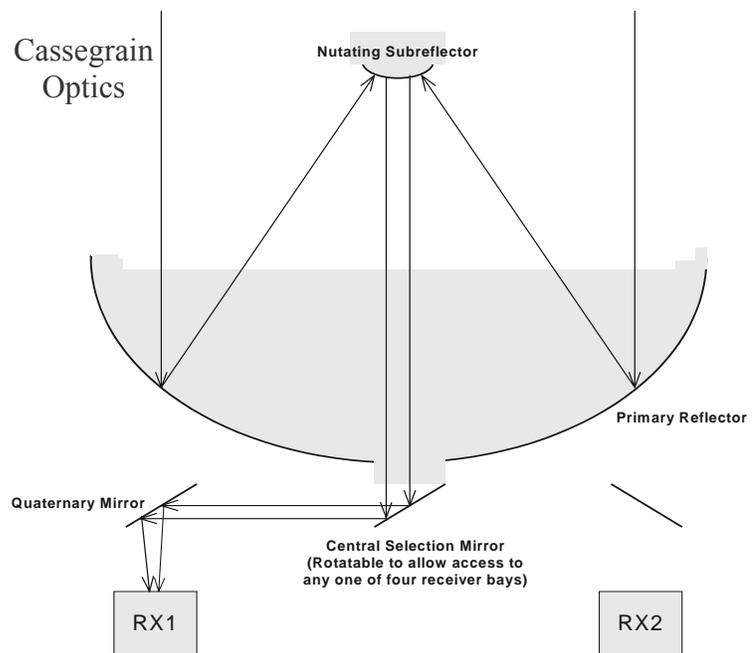

Figure 5: Basic optics of the 12 m radio telescope leading to the heterodyne detector system.

The use of the mixer and amplifier combination thus determines which sky frequency is observed. In practice at ARO, one chooses a value of ν_{LO} ("sets the LO) to get the desired sky frequency according to:

$$\nu_{LO} = \nu_{sky} - 1.5 \text{ GHz.} \tag{2}$$

The local oscillator must maintain a very stable frequency because any drifting with time would cause the sky frequency also to change. Thus before observing begins, the telescope operator will stabilize the LO frequency (to about 1 part in 10^9) using a "phase-lock loop," as well as set the LO to the desired frequency.

The IF signal is next sent a spectrometer, which divides the signal of bandwidth 1.0 GHz into a large number (say 256) of spectral frequency channels (a "filter bank"), each at a different frequency. Numerous spectra resolutions are available. Note that a complete spectrum is obtained at once, without having to take the time to consecutively scan to different frequencies.

The signals from the spectrometer are subsequently sent to a computer disk. In order to reduce the noise in a measurement (i.e. increase the signal-to-noise ratio) data is collected, or "signal-averaged," usually over a 6 minute integration period. These 6 minute "scans" are recorded to the disk under a unique scan number, which is used as an identifier for the subsequent data reduction that you will be doing. Because the stability of the electronics is excellent, one can in turn average a large number of scans to obtain one spectrum with much improved signals from two completely independent sets of receiver electronics. This duplication allows, for other types of observations, the polarization of signals to be measured, but for most observations it gives a 2-for-1 deal and nicely improves our signal-to-noise ratio.

The noise level (T_{rms}) of any measurement, which we want to minimize, follows the radiometer equation:

$$T_{rms}(1\sigma) = \frac{2T_{sys}}{\sqrt{B_W \tau}}, \tag{3}$$

where B_W is the bandwidth (or spectral resolution) of the individual channels of the spectrometer, τ is the integration time, and T_{sys} is the "system temperature," a measure of the power from the electronics and the sky that competes with the desired signal power. The intensity scale in radio astronomy is often expressed in temperature units (Kelvin), a so-called *antenna temperature*, but beware: this temperature often has little to do with any physical temperature being measured. It is rather a measure (through a thermodynamic relation) of the incident energy flux (joules/sec/Hz-of-bandwidth) falling on the antenna in the direction in which it is pointed.

The system temperature can vary with time because sky conditions change with source elevation above the horizon and with weather. Typically, T_{sys} is therefore measured before every scan or every other scan with a "cal scan." Recorded signals are actually voltages, and the cal scan determines the voltage-to-temperature conversion scale by recording the voltage of the system while looking at two known signals: a "load" at ambient temperature and blank sky position, which exhibits a colder temperature.

Another basic observing technique to correct for instrumental errors, especially those affecting the baseline (or zero level) of the spectra, is position-switching or beam-switching. In

position-switching, to remove electronic and sky instabilities, scans are actually composed of the average difference between signals taken with the dish pointed "on-source" and then pointed "off-source," going back and forth at ~30-second intervals. Beam-switching is similar, however, in addition to moving the dish between on- and off-source positions, the sub-reflector also "nutates" or wobbles back and forth. This technique can be used for point sources, such as stars, while position-switching is needed for large objects, such as molecular clouds.

Two other techniques are important at the telescope: "pointing" and "focusing." The surface of the dish is precise, but nevertheless suffers from gravitational deformations, especially as it tilts for over from the straight-up, "bird-bath" position. These deformations both de-focus the telescope, as well as cause it to aim (point) incorrectly. The pointing calibration is accomplished by observing a strong source of known position (such as a planet or continuum source), which then generates small, real-time corrections so that the telescope physically points at the desired coordinates in the sky. "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 exercise.

APPENDIX II: 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 to 6 subscan numbers for this exercise, e.g. 2.01, 2.02, 2.03, 2.04, 2.11 and 2.12 where the 01, 02, 03, and 04 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> a <scan>.<subscan>   // add each scan on a separate line
LineF> cstack   // macro to average all the data in the array

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.

The frequency of a line can be obtained using a macro.

LineF> klin   // select the line center using the cursor

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*.