

Radio Astronomy & Galactic Rotation Measurements

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Introduction

For most people, astronomy is a science driven by optical observations, historically by the human eye and more recently with large ground-based telescopes such as the twin 10-m Keck instruments on Mauna Kea or space telescopes such as the 2.4-m Hubble. Optical observations of the night sky are evidently not restricted to the human species – at least some migratory birds apparently use the positions of stars to guide their seasonal travels between summer and winter habitats. (You may speculate whether starlings are perturbed by the apparently errant behavior of a bright object such as Jupiter.)

About 80 years ago, a new window to astronomy was opened up when Karl Jansky¹⁻³ at Bell Laboratories discovered that an annoying source of interference in radio communications was correlated with the celestial coordinates of the Milky Way. This spawned very little immediate scientific interest until a ham radio enthusiast and a professional electrical engineer, Grote Reber⁴⁻⁶, decided to follow up Jansky's work with a 31.4' diameter parabolic antenna that he built in his backyard in Wheaton, Illinois with the help of two friends. The size of the dish



Figure 1. The Grote Reber 31' telescope in Wheaton, Illinois, circa 1937. Image courtesy of NRAO/AUI.

shown in Figure 1 gives a good idea why radio astronomy is pursued by relatively few amateurs. Reber was the first and only radio astronomer for a number of years, partially due to the advent of World War II. He repeated Jansky's observations of the Milky Way and discovered a number of point-like sources. Probably his most significant scientific result was the conclusion that the majority of astrophysical radio emission was generated by non-thermal sources. The end of World War II unleashed significantly more interest in this area, particularly because the technical developments for radar greatly enriched the ability to detect faint signals over a broad range of frequencies. In 1944, a Dutch astronomer, Hendrik C. van de Hulst, predicted⁷ that the hyperfine transition of neutral atomic hydrogen would lead to a sharp radio emission line at 1420.4 MHz (21.1 cm wavelength). This was important for two reasons: the origin of such a line was unambiguous and the narrow width would permit accurate relative velocity measurements via the Doppler effect. The prediction was not experimentally confirmed until almost seven years later by Ewen and Purcell⁸ and almost simultaneously confirmed by groups in the Netherlands⁹ and Australia¹⁰. The main focus of this Physics 441/442 experiment is such measurements of the H I clouds (neutral atomic hydrogen) in the plane of our Milky Way Galaxy.

Before going into further details, it might be useful to mention some of the observations at radio wavelengths that have been important for our current understanding of astrophysics and cosmology. The window for ground-based observations is roughly from 30 MHz to 30 GHz. At the low frequency end, ionization of the upper atmosphere acts as an excellent reflector of incident radiation. At high frequencies, the molecular constituents of air are extremely absorbing (witness the effectiveness of microwave ovens which operate at 2.45 GHz). This can be mitigated by observing from mountain peaks, high altitude balloons or space, depending on the wavelengths of interest (and your budget). Since 1974, four Nobel prizes have been awarded for discoveries based on radio measurements (during the same period, eleven were awarded for elementary particle physics). The list below should provide a good idea of the range of these contributions.

- 1974 SIR MARTIN RYLE and ANTONY HEWISH for their pioneering research in radio astrophysics Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars.
- 1978 ARNO A. PENZIAS and ROBERT W. WILSON for their discovery of cosmic microwave background radiation. (Also awarded that year: PYOTR LEONIDOVICH KAPITSA for his basic inventions and discoveries in the area of low-temperature physics.)
- 1993 RUSSELL A. HULSE and JOSEPH H. TAYLOR JR. for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation.
- 2006 JOHN C. MATHER and GEORGE C. SMOOT for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation.

Before leaving this subject entirely, there is one major radio astronomy discovery that has continued to elude a number of people for many years: finding extraterrestrial intelligent life.

Differences Between Optical and Radio Astronomy

For an astronomer, the optical band spans roughly between 350 nm in the near ultraviolet to 1 micron in the near infrared. At the blue end of the spectrum, atomic excitation plays a strong role in the attenuation of light (and skin cancer) while at wavelengths longer than one micron, molecular vibration levels are important, especially for H₂O and CO₂. This range also corresponds to the spectral sensitivity window of silicon-based detectors such as CCDs. Daytime astrophysical observations are pretty well precluded by the brightness of the Sun which is roughly 900 watts per square meter over this wavelength band. The brightest stars are less than 2×10^{-11} of this value. The Sun is also the brightest object in the radio sky but by significantly smaller ratios. At the L-band frequencies detected in this experiment, 1 to 2 GHz, the solar flux is about 100 times brighter than the most intense radio point source, Cassiopeia A, a 300 year-old supernova remnant in our galaxy. Since the Earth's atmosphere does not scatter such radio wavelengths appreciably, radio observations can be obtained equally well day or night (although sometimes hindered by solar flares).

Star light is predominantly generated at the photosphere and thus described approximately by the Planck spectral radiance function:

$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$$

This equation predicts the power emitted per unit area per unit frequency per unit solid angle from a surface at temperature, T. Integration over all angles from zero to $\pi/2$ multiplies this quantity by a factor of π . The peak of this function occurs when

$$h\nu = 2.821439372 kT$$

For the Sun with a photosphere temperature of 5770° K, this corresponds to a wavelength of 884 nm. At longer wavelengths where the exponential function is roughly linear in frequency, the Planck function predicts a cubic dependence of emitted power as a function of the average frequency, assuming a constant bandwidth fraction, $\Delta\nu/\nu$. This can be understood as a product of two powers of energy for the density of photon states at a given energy and one power for the bandwidth that is included, $\Delta\nu$. Thus, the thermal generation of radio waves is many orders of magnitude suppressed from the optical. In fact, the actual radio flux from our Sun exceeds the Planck spectral estimate but only by factors of the order of 20. The standard unit for expressing astrophysical radio spectral flux densities is the Jansky, $1 \text{ Jy} = 1 \times 10^{-26} \text{ joules m}^{-2} \text{ Hz}^{-1}$. To get an idea of how many radio objects are out there, the 300' radio dish at Green Bank, WV compiled the GB6 Catalog at 6 cm wavelengths (4.85 GHz) before its collapse. 75,162 objects are listed between 0° and 75° declination with fluxes greater than 18 mJy. That corresponds roughly to a density of 4 objects per square degree on the sky which is approximately the number density of 9th magnitude stars or brighter in the optical band.

Problem: Use the Planck blackbody formula to estimate the total electromagnetic solar flux at the Earth over all frequencies and the fraction within the radio band of 30 MHz to 30 GHz. Express in watts per square meter normal to the solar direction.



Figure 2a. The 300' Green Bank telescope before November 15, 1988, 9:43 pm.
Image courtesy of NRAO/AUI.



Figure 2b. The 300' Green Bank telescope after November 15, 1988, 9:43 pm.
Image courtesy of NRAO/AUI.

Hyperfine Splitting in Atomic Hydrogen

For the neutral hydrogen atom, both the electron and proton have spin and charge so they each have a magnetic moment. The quantization of the total angular momentum of the system predicts that there will be two distinct total angular momentum states, $F = 0$ and $F = 1$. The former will have the spins of the electron and the proton in the opposite direction while the latter will have parallel alignment. Simple appeal to classical arguments suggests that the angular momentum and the magnetic moment of a charged object arise from similar distributions:

$$L = \int \omega(r) r^2 dm$$

$$\mu = \int \pi r^2 \frac{\omega(r)}{2\pi} dq$$

If charge and mass are identically distributed, then:

$$\mu = \frac{q}{2m} L$$

Since L is quantized in units of \hbar , a convenient representation of this relationship is:

$$\mu = g \frac{e\hbar}{2m} \left(\frac{L}{\hbar} \right)$$

where g is a factor of order unity that includes the actual messy physics of QED and QCD. For the electron, g is very close to 2, a significant prediction of the Dirac equation. The factor of $e\hbar / 2m$ is called the Bohr magneton, μ_B , if m is the electron mass or the nuclear magneton, μ_N , if m is the proton mass.

An excellent derivation of the hyperfine energy splitting in the ground state of atomic hydrogen is provided in a paper by David Griffiths¹¹. The result to first order in the various fundamental constants is given below:

$$\Delta E = \frac{2}{3} g_e g_p \frac{m_e}{m_p} \alpha^4 m_e c^2 = 9.428 \times 10^{-25} \text{ J}$$

Evaluating this expression leads to a value for the transition frequency:

$$f = \frac{\Delta E}{2\pi\hbar} = 1422.8 \text{ MHz}$$

In fact, due to higher order QED diagrams, the frequency is somewhat less:

$$f_{\text{observed}} = 1420.4057517667 \text{ MHz}$$

One slightly puzzling aspect of this phenomenon is that in the $F = 1$ state, the magnetic moments are antiparallel while for $F = 0$, the moments are parallel. Griffiths provides an explanation for why the singlet state should have the lower energy although it was not entirely convincing to this reader.

The calculation of the lifetime of the hyperfine triplet state can found in section 11.5.2 of a book by Ernest Abers¹². Again, to first order in the fundamental constants, the transition rate is given by:

$$\Gamma = \frac{\alpha}{3} \left(\frac{\Delta E}{m_e c^2} \right)^3 m_e c^2 = \frac{1}{3} \left(\frac{2g_e g_p m_e}{3m_p} \right)^3 \alpha^{13} m_e c^2 = 3.04 \times 10^{-49} \text{ J}$$

which translates to an expected lifetime:

$$\tau = \frac{\hbar}{\Gamma} \cong 11,000,000 \text{ years}$$

By comparing the intensity of radiation from the Sun and from the H I emission in the Galaxy, you can obtain a crude estimate of the galactic mass that is in the form of free atomic hydrogen.

c	299792458 m/s
\hbar	$1.054571726 \times 10^{-34}$ J s
e	$1.602176565 \times 10^{-19}$ C
α	$7.2973525698 \times 10^{-3}$
$m_e c^2$	$8.18710506 \times 10^{-14}$ J 510998.928 eV
m_p/m_e	1836.15267245
g_e	2.00231930436152
g_p	5.585694712

Table I. Useful fundamental constants. (From NIST)



Figure 3. The Small Radio Telescope on the roof of Angell Hall.

The Small Radio Telescope (SRT)

The Small Radio Telescope (SRT) that will be employed in this experiment is installed on the roof of Angell Hall. It is physically accessible when accompanied by either a Physics 441/442 staff member or instructor. Fortunately, the telescope is completely controllable via a remote PC installed on the 5th floor of Angell Hall in room 5190. This, in turn, is remotely accessible via Ethernet from anywhere else as long as you have installed the Microsoft Remote Desktop Program (RDP) with the appropriate login name and password.

The SRT was designed in 2000 by staff members at the MIT Haystack Observatory with the support of an NSF grant. The goal was to provide undergraduates with a hands-on opportunity to learn about radio astronomy. To keep the costs consistent with the limited resources of undergraduate teaching budgets, the design centered around a modest 90" diameter commercial satellite antenna that also reduced the requirements for a fully steerable mount. The unit on the roof of Angell Hall was bought and installed in 2000 although a few years ago, the receiver was apparently damaged by lightning. The receiver was replaced in March 2011 and since that time, we have been exploring the observational capabilities of this system. Unfortunately, none of the components of the SRT are currently being manufactured so if anything breaks, repair is difficult if not impossible. The 2-axis antenna motor drive is exceptionally touchy and liable to irrecoverable failure. This instrument is now a shared facility between the Astronomy and Physics Departments so be aware that other classes may be trying to obtain observations simultaneously. Protocols for handling these situations will need to be developed.

The SRT antenna is mounted in an az-el configuration (azimuth-elevation). This makes the cost and weight considerably less. Facing south, the minimum elevation is 8°; facing north it is 20°. These limits are depicted in Figure 4 below and must be kept in mind when planning observing runs. The program which computes the position of interesting sky objects is called *radio_coords* and runs under the IDL computation package. The input to this code is simply the date and time of interest; if this is the present moment, simply enter a carriage return. There is some inevitable overhead to learning how to use a different computation package but the efficiency of IDL for a wide variety of tasks makes it worth the investment.

From solar observations carried out in June 2011, we have found that there are significant mount pointing errors that vary with the telescope azimuthal position. For measurement of H I emission in the Galactic plane, these are not important because the source is quite diffuse. For point sources, it is an important aspect that must be included when constructing an observing command file. These offsets are graphed in Figures 5a and 5b below.

A slightly annoying problem has been discovered with the SRT receiver. Large amplitude spikes are frequently observed at three equally spaced frequencies. For frequency mode 4, these correspond to channels 20, 66 and 112. The spikes slightly spill into the adjacent channels. Mostly, they can be ignored. However, if you really want to measure the flux at these particular frequency values, simply set the center frequency value several channels higher or lower and repeat the measurements to fill in the bad values. At the moment, the cause of this problem is unknown but is likely associated with the superhetrodyne local oscillator.

Most of what you need to know about the SRT can be found in the Small Radio Telescope Operator's Manual which can be found at:

<http://www.haystack.mit.edu/edu/undergrad/srt/SRT%20Software/SRTManual.pdf>

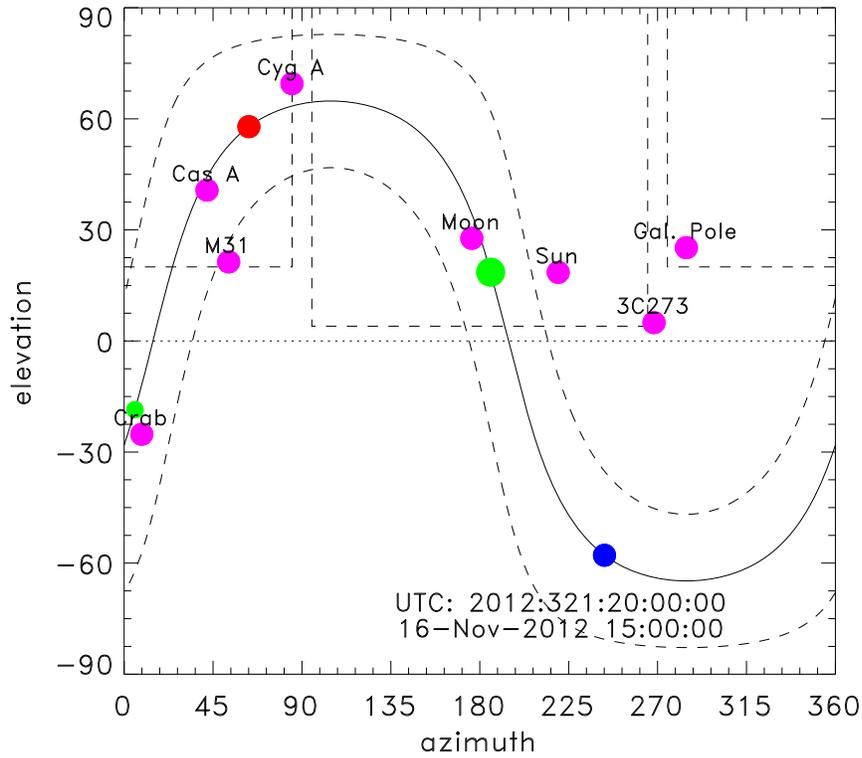


Figure 4. The graphic output of the IDL program, *radio_coords*. The green dots indicate the Galactic center (large) and the Galactic anti-center (small). The red and blue dots point to galactic longitudes of 90° and 270° respectively. The sky coverage accessible to the antenna mount lies above the straight dashed lines. The difference between local time and GMT (UTC) is either 4 hours (in the summer) or 5 hours (in the winter).

```

UTC: 2011:238:15:15:12
    26-Aug-2011 11:15:12

```

Name	RA	Dec	Azim	Elev	
Sun	154.992	10.385	125.344	45.459	
Moon	120.941	17.170	176.580	64.826	0.084 -
Cas A	350.858	58.800	334.579	19.703	
Crab	83.633	22.014	247.137	53.971	
3C273	187.278	2.052	103.833	17.592	
Cyg A	299.868	40.734	359.708	-6.956	
M31	10.685	41.269	312.472	15.413	
Gal. Ctr	266.405	-28.936	74.103	-60.296	
Gal. Pole	192.859	27.128	79.014	29.613	

Table II. Printed output from the IDL program, *radio_coords*. This information as well as the coordinates of the Galactic plane is also available in the file, *radio_coords.txt*.

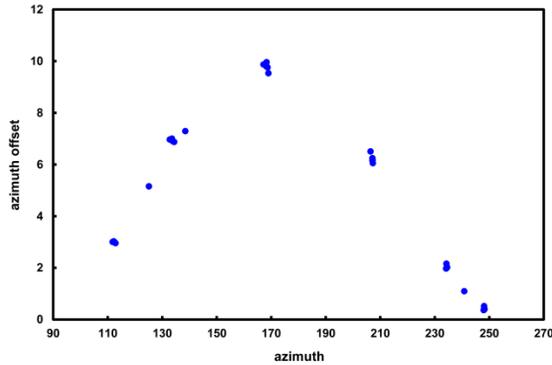


Figure 5a. Azimuth axis errors determined from solar observations.

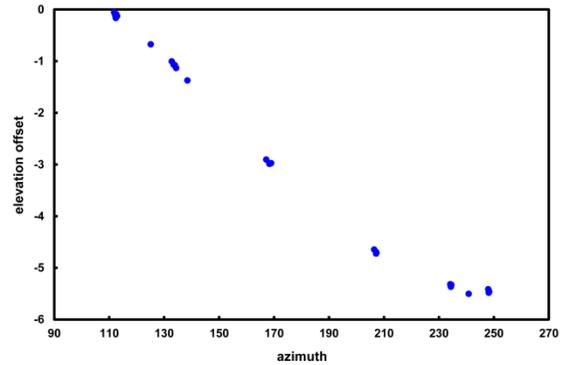


Figure 5b. Elevation axis errors determined from solar observations.

A booklet of relevant manuals and significant articles relevant to this experiment will be kept in the Physics 441/442 lab classrooms.

Operating the Small Radio Telescope

First and foremost, the SRT is a joint facility belonging to both the Astronomy and Physics Departments. The usage will be shared on a 50-50 basis between our two departments and so the primary scheme for time allocation is odd days of the month go to Physics and even days go to Astronomy. This won't work perfectly for all parties all of the time so day-to-day exceptions will be negotiated between the concerned faculty members. For this reason, it is absolutely essential to file an observing plan with the Physics 441/442 instructor prior to logging into the SRT control computer. Remember that more than one Physics 441/442 group may be seeking access to this system in the same time frame. Please provide suitable advance warning! Failure to abide by these rules will eliminate this experimental facility for student use.

The control of the SRT is entirely through the desktop PC located on the 5th floor of Angell Hall. The computer name is PHYS-ADVLAB7SRT and, should you need it, the IP address is 141.211.54.247. The OS is Windows 7 and the login name should be specified as umrootphys-advlab2. The password will be supplied on request. It is expected that interaction with this system will be entirely by remote Internet connection.

Since access to Room 5190 of Angell Hall is by special key only, it is expected that you will login via the Windows Remote Desktop application. On the computers available in the Physics 441/442 classrooms, this can be initiated by double-clicking the SRT_PC icon on the Desktop window.

On login, you should see an icon with an image of the SRT. Click on that to initiate the SRT control code. A DOS command window should appear immediately followed by a much larger window that looks similar to Figure 6 below.

For a very large number of reasons, it is strongly advised that the principle means of communicating with the SRT control program should be via text scripts. The SRT software was written with some rather inconvenient defaults for file names. Command scripts are expected to have file extensions of “.cmd” while output data is written to “.rad” files. In the Windows OS, a *cmd* file is generally reserved for executing a command sequence in the primitive DOS environment. To get around this issue, initiate the Windows *Notepad* editor found under “Accessories”. A “rad” file can be viewed with the same utility. Although you are free to use any

such use.) When designing an SRT observing script, make sure the objects of interest are visible at the requested times. Report any fatal operational errors to the Physics 441/442 instructor immediately via E-mail. Please make sure that the conclusion of any observing run includes a command to stow the telescope to its home position.

Another dedicated read-only directory is C:\Users\Public\Desktop\Astrophysics\IDL_lib. This is the repository for the IDL astronomy library written principally by people at NASA/Goddard.

- run.bat* Text file which invokes the SRT control program by compiling and loading Java source code.
- srt.cat* Text file read by srt.exe to initialize critical tables. This file contains local geodetic coordinates of the telescope, a list of source coordinates and the antenna mount limits.
- xxx.cmd* Text file containing an observing script. Set 'xxx' to a string that will identify date and user. This file must be edited with a program such as *Notepad*.
- yyy.rad* Text file containing data obtained from an SRT observing sequence. Set 'yyy' to a string that will identify date and user.

Special files encountered with operating the SRT

An undocumented trick for *.cmd files: To embed a comment that gets transmitted to the output *.rad data file, insert `:00 this is a comment that will appear in the data file`

Observations with the SRT

The Sun is the brightest radio source in the sky and accessible throughout the day. To get some experience with the SRT system, make a raster scan of observations around the nominal Sun coordinates using the offset commands as shown in the file, *sun_seek_2011_06_04.cmd*. The sequence in this particular file was designed to sample every 2° along both azimuth and elevation axes. Remember that for the azimuthal direction, the actual change in space angle is the change in azimuth multiplied by the cosine of the elevation. The data from this exercise can be used to measure the telescope angular resolution which is considerably broader than the 30 arc-minutes of the solar disk. The command file performs a 9 × 9 raster scan around the nominal Sun coordinates. Note that you may want to make allowances for the mount positioning errors shown in Figure 5. The SRT control code includes a function, *npoint*, which performs a similar function but limited to a 5 × 5 scan.

The major task for this experiment is the measurement of the galactic rotation of the Milky Way by observing the Doppler shift of the 21-cm atomic hydrogen hyperfine transition. The basic problem can be related to the kinematic description of a merry-go-round. You sit on an object near the rim around 8 Kpc from the center which is rotating in a clockwise direction as seen from above. If you look to the left of center at galactic longitudes between 0° and 90°, objects will be receding from you while to the right of center at galactic longitudes between 270° and 360°, objects will be approaching. As shown in Figure 6 below, from Ann Arbor we only have a good view of stuff on the left. The description of the technique is given in detail in two

memos^{13, 14} written by the MIT Haystack staff members Alan Rogers and Larry Kimball and also published in a laboratory manual¹⁵ by Laura A. Whitlock and Kiley Pulliam. This will require ten measurements of the H I emission taken at 10° intervals of galactic longitude between 0° and 90° for 0° galactic latitudes. You will need to use the IDL program, *radio_coords*, to plan your observing program. For each observing direction, find the Doppler shift for the fastest receding gas corresponding to the material closest to the galactic center. Follow the memo instructions for

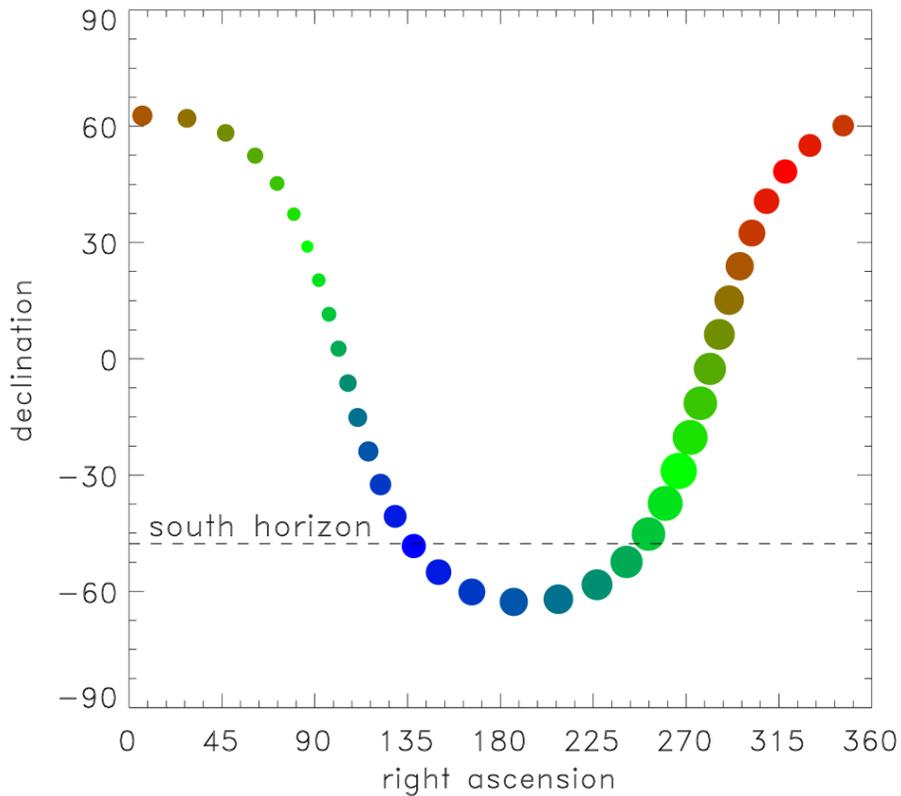


Figure 6. Celestial coordinates of the galactic disk. The color and size of the dots indicate the direction and relative velocity of each 10° interval in galactic longitude in the plane of the disk. The color code is similar to Figure 4. Note that most of the third quadrant with l between 270° and 360° is never accessible from Ann Arbor.

reducing the data to a plot of orbital velocity as a function of radial distance from the center. You should estimate use the magnitude of each velocity to estimate the total amount of matter contained within the corresponding orbital radius. Careful measurements of stellar densities within our galaxy indicate that the majority of stars are well inside the 8 Kpc orbit of our Sun. Comment on whether stars alone could lead to the shape of the galactic rotation curve that you have measured.

Most of the references listed in this experimental description have been assembled into a bound notebook available in the Physics 441/442 classrooms. In addition, books by Bernard Burke & Francis Graham-Smith¹⁶, Frank Shu¹⁷ and Gerrit Verschuur¹⁸ are highly recommended for additional background information about astronomy and radio astronomy in particular.

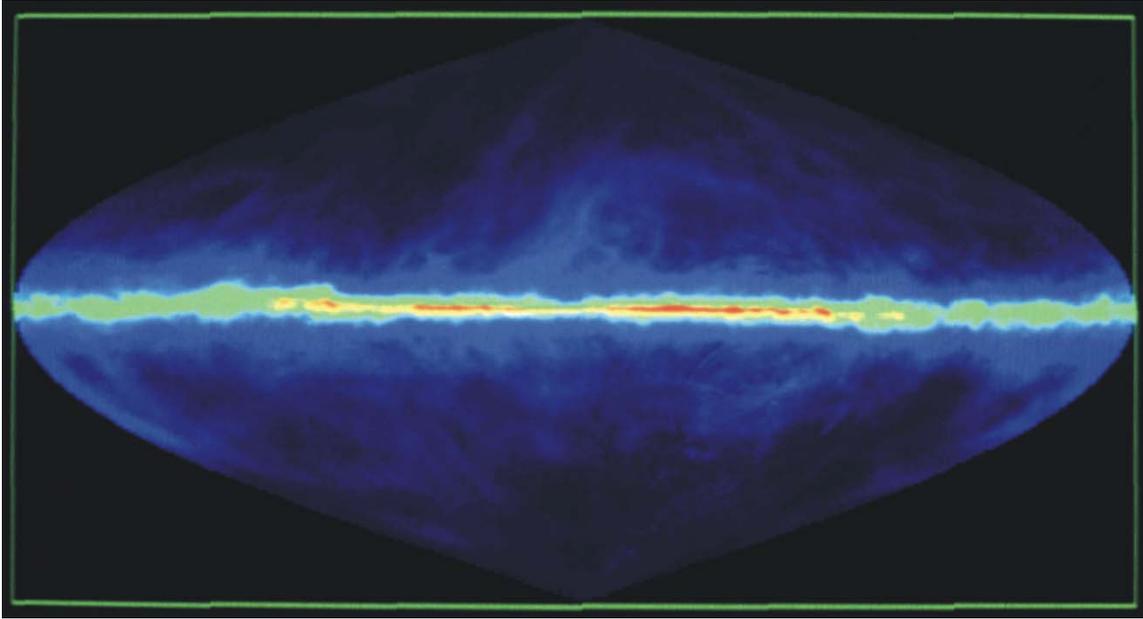


Figure 7. The Milky Way Galaxy imaged by 21-cm H I radio emissions. Image courtesy of NRAO/AUI.

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Appendix A: SRT script commands (from SRT online help facility)

```
command file rules:          (filename srt.cmd

1] reads one line at a time skipping blank lines, and lines
which start with * and lines with past times
2] stops at and executes any line with current or future time
time format:
  line starts with yyyy:ddd:hh:mm:ss and is followed by cmd
alternate format:  LST:hh:mm:ss  cmd
current time format:  :  cmd
current time plus n seconds format:  :n  cmd
each line MUST start with time or : or * for comment
command keywords:          items in [ ] are optional
sourcename,mode,radec,azel,galactic,offset,stow,calibrate,noisece
al,record,freq,roff
  sourcename (any name in catalog) [mode]
  mode n(for 25_point scan)      b(for beamswitch)
  radec hh:mm:ss [sign]dd:mm:ss [epoch] [mode]
  azel az_deg el_deg
  galactic glat_deg glon_deg
  offset azoff_deg eloff_deg
  stow
  calibrate (for vane) or noiseceal (for noise diode)
  record [filename] [recordmode(0=normal,1=short,2=add
vlsr,3=special,4=summary only)]
  roff (turns off record)
short - suppresses recording cmds
  freq frequency num [spacing] - for analog receiver
  freq frequency digitalmode - for digital receiver
Note that 25_point scan runs only once while beamswitch until
next cmd
For example:
: Sun
:60
:600 Sun n
: stow
goes to the sun,waits 60 seconds,does 25 point
and after 600 seconds goes to stow
Note that the seconds to wait is right next to the ":"
and otherwise there is a space before the command
```

A command file can be checked by running java in simulate mode
-see help on cmdline options
another name for a command file can be entered by clicking
on the text area.