

# MAPPING THE HI LINE: THE GALAXY AND SUPERSHELLS

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## 1. GOALS

The goals of this lab consist of some collection of the following, depending on the project chosen:

- Perform a large-scale observing survey project balancing considerations of telescope time, integration time, sky coverage, data reduction, report writing, and personal time commitment versus research goals and quality of results and their presentation.
- Use the collected data to infer astrophysical phenomena or quantities such as the properties of supernova-driven interstellar supershells and the Galaxy.
- Present data and/or using greyscale and/or color images.
- Learn about using colors in computer graphics including plots and images.
- Learn about problems in using color for presentations, specifically contrast issues and color-blindness.

## 2. INTRODUCTION

Diffuse atomic gas permeates all corners of interstellar space. On the largest scales, its distribution reveals a lot about Galactic structure and dynamics. On smaller scales, its morphology is dominated by shocks from energetic stellar winds and supernovae. On still smaller scales, magnetic fields, pressure differences, and thermal instability shape the gas into thin filaments and sheets. On still smaller scales, the densities get large from self-gravitation; the gas turns molecular and stars form. The dense regions where Star formation occurs occupy a small fraction of the interstellar volume. In contrast, the atomic gas (HI) resides in less-dense regions that occupy large fractions of interstellar space and you see Galactic HI wherever you point the telescope.

For this lab, we outline several projects to map interesting structures in HI using our 4.5-m diameter Leuschner dish. The HI projects fall into two categories. One explores large-scale Galactic structure and dynamics by obtaining HI spectra along great circles, presenting the data as position-velocity images, and interpreting those maps as discussed below. The other category maps specific interstellar structures (e.g., expanding shells produced by multi-supernovae) by sampling a grid of spectra over a large area, presenting the data as grey-scale images of velocity-integrated line intensity (i.e., antenna temperature  $T_A$ ) or as images in which image brightness indicates velocity-integrated  $T_A$  and color indicates velocity.

We'd like each group to pick a single project and carry it through to completion by the time the lab reports are due, which is the last day of class (May 1). All of the HI projects involve making maps and images. One of the features of this lab is to learn about image processing and using colors in images.

For the great-circle projects (§6 and §8), we gain large angular scale information in the sky by observing on great circles. Getting nice results requires data over the largest portions of the great circles you can get. For a full 360-degree circle, that's 180 pointings at  $2^\circ$  spacings. Mostly, though, we can't cover a full great circle because some of the circle lies too far south, so we do as much as we can.

## 3. SCHEDULE

The end of the semester is approaching like a freight train. Here's our schedule.

1. Week 1: Pick a group project. Figure out the RA and Dec boundaries of your object, when the object is up, and how you sample the area with telescope pointings. Coordinate with other groups to figure out how you can share telescope time. Devise a scheme for scheduling observations of all the points in your map. Begin the process of obtaining and reducing your map data.

Obtain some frequency-switched test spectra, in particular at our canonical comparison po-

sition at Galactic coordinates  $(\ell, b) = (120^\circ, 0^\circ)$ . We will compare the spectra of all groups at the class on 10 April, and if your group doesn't have a spectrum to show this will be considered *very* bad form.

2. Week 2: Get as much data as you can. Reduce the data. Decide what projection you will use to present your maps; create the map plane and populate it to the extent possible with the data you've obtained. You won't have all of your data, but begin the map-making process anyway (§15); this process begins with making a data cube.
3. Week 3: Get the rest of your data. Figure out how you want to present the data as images. Make some first-try images.
4. Week 4: Finalize data. Make final images. Write report. Report is due the last day of class, 1 May.

## 4. CONTROLLING THE LEUSCHNER TELESCOPE

### 4.1. Connecting to the heiles Computer at Leuschner

Use `ssh` to connect to Leuschner, like this:

```
ssh -XY radiolab@leuschner.berkeley.edu -p 31
```

Use the password we give you in class.

All external users use the `radiolab` account. You don't want a subdirectory that contains files of other users, so immediately after logging in create a subdirectory for yourself and do all of your work there. For example, if your group is named DREAMTEAM:

```
radiolab@heiles:~> mkdir dreamteam
radiolab@heiles:~> cd dreamteam
radiolab@heiles:~/dreamteam>
```

The prompt tells you what subdirectory you're in; if in doubt, type `pwd`. All of the canonical editors<sup>1</sup> and Python/IPython are available to you, just as on the `ugastro` network.

### 4.2. Using VNC at the heiles Computer at Leuschner

For running observing sessions that run automatically for long periods of time, we strongly recommend using VNC for the reasons explained in class. In particular, if everyone uses the same

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<sup>1</sup>When using `emacs`, using the `-nw` option will eliminate latency and delays, and your associated frustrations.

VNC Leuschner window, we will avoid having more than one group observing at a time. We have set up a particular VNC server on the heiles computer at Leuschner, which is number 5901. You access it by, first, establishing the connection:

```
ssh -L 59XX:127.0.0.1:5901 -p 31 -N -f radiolab@leuschner.berkeley.edu
```

It will require a password; use the password for the **radiolab** account given in class. Here **XX** is a number of your own choosing; it refers to a port on your local machine. If it responds by saying **bind: Address already in use**, then choose a different number and try again. Once you find a number that works, use it in subsequent connections. *This ssh command needs to be done only once<sup>2</sup>.*

Having done that first step, on all subsequent occasions access the Leuschner/heiles VNC window with the command

```
vncviewer -shared localhost::59XX
```

It will require a password; use the password for the radiolab account's VNC session given in class. Leuschner's VNC window should pop up on your screen, and you can access and create terminals on this window in the usual way. The function key F8 gives a short menu of available actions, such as quitting the VNC viewer. Use of the **-shared** option allows multiple users to access the VNC window simultaneously. For example, if you are in the 5th floor lab and begin observing, you can leave your VNC session running and you can go home and access the same VNC window from there.

### 4.3. Python Procedures for Controlling the Dish

The `ugradio.leusch` module provides an interface for controlling the Leuschner dish. In particular, the `LeuschTelescope` class should look familiar to you; it works basically the same as the `Interferometer` class you used in the previous lab.

1. `LeuschTelescope.get_pointing()` returns the current (alt,az) of the dish, in degrees.
2. `LeuschTelescope.point(alt,az)` moves the telescope to a specified alt, az in degrees.
3. `LeuschTelescope.maint()` moves the telescope to maintenance position.
4. `LeuschTelescope.stow()` moves the telescope to stow position.

If you find you need the coordinates of the Leuschner Educational Observatory, they are stored in `ugradio.leo`.

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<sup>2</sup>Unless the remote machine had to be rooted for some reason; this will probably not happen during the duration.

#### 4.4. Python Procedures for Taking Data

The Leuschner dish has a noise diode at the front that you can turn on/off for calibration purposes.

1. `ugradio.leusch.LeuschNoise()` instantiates an interface to the noise diode (it's controlled by a Raspberry Pi).
2. `LeuschNoise.on()` turns the noise source on.
3. `LeuschNoise.off()` turns the noise source off.

We also have an l.o. that you can shift around for calibration purposes. It's actually the same Agilent l.o. you used in the horn lab, only we've unplugged it and moved it to Leuschner. This means you can control it with `ugradio.agilent`, same as before, but connect to the `heiles` computer, instead of the lab machine that was hosting it. Since `heiles` is the computer you are already logged into, use the address 127.0.0.1 (which means "self").

1. `ugradio.agilent.SynthClient(host='127.0.0.1')` instantiates an interface to the l.o.
2. `SynthClient.set_frequency` changes the l.o. frequency.

Next, we need to read data from the spectrometer attached to the Leuschner dish. This spectrometer is controlled by the `leuschner` module outside of `ugradio` (e.g. `import leuschner`). As always, for more information, read the `leuschner` code documentation.

1. `leuschner.Spectrometer('10.0.1.2')` instantiates an interface to the spectrometer at the specified IP address.
2. `leuschner.Spectrometer.int_time` tells you how long each spectrum is integrated for.
3. `Spectrometer.read_spec('out.fits', N, (ra,dec), 'eq')` will read N spectra and store the output in a FITS file, writing the ra/dec coordinates into the header of the file. Note that this does **not** point the telescope; it just documents where it is pointed in the file. You could also provide `read_spec('out.fits', N, (glat,glon), 'ga')` to write galactic coordinates into the FITS header, if you'd like.
4. `Spectrometer.check_connected()` allows you to check that you are ready to take data.

Finally, once you have a saved FITS file, you need to be able to get your data out of it. For this, we use the standard module `pyfits`.

1. `f = pyfits.open('out.fits')` opens your file and returns you a handle to it.

2. `f[0].header` holds lots of metadata about your observation. You can `print f[0].header`, or you can convert it to a dictionary with `dict(f[0].header)`.
3. `f[1].data['auto0_real']` returns the first spectrum for the first polarization, `f[1].data['auto1_real']` returns the first spectrum for the second polarization, and `f[N].data['auto0_real']` returns the  $N^{\text{th}}$  spectrum for the first polarization.

## 5. ON MAPPING AREAS: HOW TO SPATIALLY SAMPLE

### 5.1. Sampling Your Sky Area

All of the HI projects examine the angular dependence of the 21-cm line profile, so you need closely-spaced observations to make a map or an image. How closely should the observations be spaced? The usual criterion is two samples per HPBW (Half-Power BeamWidth), because observing at more closely spaced angles just gives redundant information and takes extra time, while more widely spaced angles loses small-scale structural information. (This statement can be justified more exactly by Fourier transforming the structure of the sky in terms of angular frequency and then imposing the Nyquist criterion...). The HPBW is almost  $4^\circ$ ; so a spacing of  $2^\circ$  is about right.

For the mapping projects (not the great-circle ones), we need to cover areas of 1000 to 2000 square degrees. Consider the Orion-Eridanus Superbubble (§10 below), which wants to map the region covering roughly ( $\ell = 160^\circ \rightarrow 220^\circ$ ,  $b = -70^\circ \rightarrow -10^\circ$ ). You might think you'd set up a regular grid in  $(\ell, b)$  with  $(\Delta\ell, \Delta b)$  both equal to  $2^\circ$ . That's fine for  $\Delta b$ , but you'd be sampling too closely in  $\ell$ . That's because the true (great-circle) angular distance between two points is  $\Delta\ell \cdot \cos(b)$ ; there's a foreshortening for  $b \neq 0^\circ$  (e.g.: when you're at the Earth's North Pole, you can go completely around a small circle of constant  $b$  with just a few steps.). So you can save lots of observing time by observing at  $\Delta\ell = \frac{2^\circ}{\cos(b)}$  instead of  $\Delta\ell = 2^\circ$ .

The true angular area is not the total extent in  $\ell$  times the total extent in  $b$  because of the foreshortening discussed in the above paragraph. So the actual angular area of the Orion-Eridanus area isn't the range in  $\ell$  times the range in  $b$ , i.e.  $60^\circ \times 60^\circ = 3600$  square degrees (which would require 900 pointings), but rather only about 2800 square degrees. At  $2^\circ$  sampling, that's about 700 pointings.

These projects require what seems like a lot of pointings, but—hey!—the telescope is automated. With the magic of a computer-controlled telescope you can do these observations in just one or two days. But it will require planning and coordination with other groups—all of you are in the same boat! (Or should we say, “in the same dish”?)

## 5.2. Recommended Commands

For actually taking the data at a particular position, we recommend the following sequence of commands for each position:

```
find the (ra, dec) for your position. you can use 'astropy' if you wish
Nspectra = ??? (number of 0.7-sec spectra to obtain--pick an appropriate number)
telescope.point(alt,az) at the alt/az corresponding to the position
    of your chosen ra/dec at the midpoint of your upcoming observing time
    so that the midpoint of the integration coincides with the position of the source.
filename = jjjjjjj.jjjjjj\_pt0000\_nd1.fits or something similar that encodes
    enough useful information (JD, pointing, noise diode, etc.) that you can find
    what you need after making many observations.
spectrometer.read\_spec(filename, Nspectra, (ra,dec), 'eq') takes and records the data
```

You are strongly advised to look at the documentation of these procedures before using them!

## 5.3. Beware Operating near Azimuth 0/360!!

If the azimuth of the current position is  $6^\circ$  and of the next one is  $354^\circ$ , the telescope has to rotate nearly  $360^\circ$  in azimuth, which takes a long time! You don't want to make this transition more than once! (or at all, if you can manage it). Note: the telescope will reliably point in the  $370^\circ$ -wide azimuth range  $-5^\circ$  to  $365^\circ$ —but not outside this range.

## 5.4. Beware Operating Above Altitude 85 and Below/Near 14!!

The telescope cannot point above altitude  $85^\circ$ . And it cannot point below  $14^\circ$ . When you are at low altitude, you might be seeing the ground!

## 6. THE GALACTIC PLANE: THE GREAT CIRCLE AT LATITUDE ZERO ( $b = 0^\circ$ )

Point the telescope at a series of Galactic longitudes ( $\ell$ ) along the Galactic plane (Galactic latitude  $b = 0^\circ$ ), over the full longitude range that is observable for our telescope. Getting nice results requires data over the largest section of the Galactic plane you can get, which is roughly (or somewhat less than)  $\sim -10^\circ \lesssim \ell \lesssim 250^\circ$ . This observation has two science goals:

1. *The Galactic rotation curve.* Determine the rotation curve of the Galaxy for the portion of the Galaxy inside the Sun and use the result to estimate the *gravitational* mass  $M_{\text{grav}}$  of



the Galaxy that lies inside the Solar circle; for this, you just assume the usual  $v^2 = \frac{GM_{grav}}{R}$ . In fact, you can even get the radial dependence  $M_{grav}(R)$ ! Also, use your observations to estimate the *gaseous* mass  $M_{gas}(R)$  of the Galaxy. What fraction of the total Galactic mass comes from interstellar gas? For this you'll need to know the radius of the Solar circle: it's 8.5 kpc. See *Commentary* below for a discussion.

2. *The Galactic center.* Our Galactic center, like others, has a big black hole, with infalling matter and jets and lots of anomalous velocities. You can see a lot of this activity in your map. Using the spatial extents and the velocities, you can estimate a black hole mass. To get an accurate estimate, you need to look at motions of matter lying really close to the black hole, which you can't do because you don't have the angular resolution. But you can at least make an estimate!
3. *Spiral Structure of the Galaxy.* All your life, you've been told that we live in a spiral galaxy. Are they lying? In principle, to detect spiral structure you make a position-velocity plot along the Galactic plane [that's the image  $T_A(\ell, V_{LSR})$  for  $b = 0^\circ$ ]. Bright regions are regions of excess density—or regions in which lots of HI is packed into a narrow velocity range (see §14.1 below).

Do you see spirals in your position-velocity plot? How do you tell? There's only one easy way. Make a model of a spiral arm and see how it projects onto position-velocity space. To do this, you need to know the rotation curve. You've measured it for the inner Galaxy; for the outer Galaxy (outside the Solar circle) assume that the rotation curve is constant beyond the solar circle [ $V(R)=220$  km/s for  $R > 8.5$  kpc]. In polar coordinates, the equation for a spiral arm is

$$R_{arm} = R_0 e^{\kappa(\phi - \phi_0)} \quad (1)$$

where  $R_0$ ,  $\kappa$ , and  $\phi_0$  are free parameters;  $\kappa$  is the tangent of the *pitch angle*. You project this into position-velocity space using equation 8 and your knowledge of the Galactic geometry.

*Comment:* Finding spiral arms inside the Solar circle is very difficult, and has thwarted efforts by astronomers over the past several decades. Finding them in the outer Galaxy is not so bad.

## 7. IS THE GALACTIC PLANE FLAT?

External galaxies are often distorted (like the brim of a Fedora). These distortions are probably produced primarily by nearby neighbors. How about our own Galaxy? To determine this we want to look at the vertical structure of the Galactic plane and see where the peaks occur; a flat Galaxy would everywhere have the peaks at  $b = 0^\circ$ .

The most comprehensive way to observe and display these distortions is with a map that covers the biggest possible swath in Galactic longitude  $\ell$  for the range of Galactic latitude ( $b$ ) from  $-20^\circ$  to  $+20^\circ$ . This is a huge area—almost  $10^4$  square degrees! At  $2^\circ$  sampling, you’d need  $\sim 2500$  profiles. To make the project more manageable, you can increase the increment in  $\ell$ , say to 4 degrees, while keeping the same, fully-sampled increment in  $b$ . Resolution in  $l$  is less important because—like a fedora—the warp doesn’t change rapidly with  $l$ .

This project affords a great opportunity to make a spectacular color image in  $(\ell, b)$  coordinates: brightness showing the amount of gas, color the Galactic rotation. Officially, the science goals here are to estimate the thicknesses of the Galactic disk and, also, to obtain an approximate Fourier representation of the warp—which is not so straightforward given the absence of data in the “Southern” Galaxy.

## 8. THE GALACTIC POLES: GREAT CIRCLES AT CONSTANT LONGITUDE $\ell$

How is the interstellar gas distributed within the Galaxy—for example, is it “disklike” or more spherically distributed? Are there any systematic motions other than just “Galactic rotation”? (You’d be surprised!). To answer these questions, determine the column density and mean velocity of interstellar gas as a function of Galactic latitude  $b$ .

To answer this completely you’d need to do a sky survey! That’s a big job. So let’s do something easier. We have one project (§6) that looks around a great circle, the Galactic equator (constant  $b$ ). Other projects could check out one or more orthogonal great circles (at constant longitudes  $\ell$ ) going from one Galactic pole to the other and back again (or, if not the whole 360 degree circle, as much as possible). Particularly appropriate sets of constant-longitude great circles are the pairs  $\ell = (220^\circ, 40^\circ)$  (partly because you can get the whole great circle) and  $\ell = (130^\circ, 310^\circ)$  (because at positive latitudes there’s weak high-velocity gas).

The science goals here are to characterize the thickness of the gas layer and to determine the vertical kinematics of the gas, and if possible an estimate of the energy involved in the vertical motions.

## 9. MAPPING THE NORTH CELESTIAL POLE

The region near the North Celestial pole contains a large shell, probably produced by one or more supernovae, and also has angular scales that are well-matched to our telescope and the available time for your project. For this, you’d map the region covering roughly ( $\ell = 105^\circ$  to  $160^\circ$ ), ( $b = 15^\circ$  to  $50^\circ$ ). Interesting features should produce antenna temperatures  $\sim 10$  K. This is about 1600 square degrees and, with 2 degree spacing, requires about 400 profiles. With our telescope, this is probably the most spectacular and contrasty object we can map in the sky.

## 10. MAPPING THE ORION-ERIDANUS SUPERBUBBLE

The “Orion-Eridanus Superbubble” was, and continues to be, produced by energetic stellar winds and supernovae that were located in immediate vicinity of the Orion nebula. For this, you’d map the region covering roughly ( $\ell = 160^\circ \rightarrow 220^\circ, b = -70^\circ \rightarrow -10^\circ$ ). Interesting features should produce antenna temperatures  $\sim 20$  K. This is almost 2800 square degrees and, with 2 degree spacing, requires almost 700 profiles. See §5!

The goal here is to map the HI in the 3-d space of  $(l, b, v)$  (that’s Galactic longitude, latitude, and velocity) and then present the results in one or more color images to show the hollowed-out shell with the swept-up gas piled up at the edges.

## 11. MAPPING THE NORTH POLAR SPUR and its associated EXPANDING HI SHELL

This is a huge shell produced (and continuing) by several energetic stellar winds and supernovae that were located in the Sco/Oph association of stars. The shell contains not only HI but also relativistic electrons, so the shell is visible in both the 21-cm line and synchrotron emission. We can’t easily see the latter, but we can see the HI—and the pattern of its velocity follows that of an expanding shell.

For this, you’d map the region covering roughly ( $\ell = 210^\circ \rightarrow 20^\circ, b = 0^\circ \rightarrow 90^\circ$ ). (The longitude range is  $170^\circ$ :  $210^\circ \rightarrow 360^\circ$  plus  $0^\circ \rightarrow 20^\circ$ ). This is roughly 1/4 of the whole sky, so this is a huge area—almost 10000 square degrees! (This shell has an angular diameter of  $120^\circ$ ). But (unfortunately) you can’t measure the equivalent 2000 HI profiles because most of this area is too far south. At least, this makes the project do-able! In doing your observations, you need to cover as far south as you possibly can. See §5!

The goal here is to map the HI in the 3-d space of  $l, b, v$  (that’s Galactic longitude, latitude, and velocity) and then present the results in one or more color images to show the hollowed-out shell with the expanding swept-up gas piled up at the edges.

## 12. MAPPING A BIG HIGH-VELOCITY CLOUD

When we look up, away from the Galactic plane, we see infalling gas—some a very high velocities. It’s called “High-Velocity Gas”. The line is weak (about 1 to 1.5 K), so you need high sensitivity—you need to use much longer integration times than for the above projects, at least a few minutes per point. This project needs to map the region bounded roughly by ( $\ell = 60^\circ \rightarrow 180^\circ, b = 20^\circ \rightarrow 60^\circ$ ). This is about 3700 square degrees and needs about 900 profiles at  $2^\circ$  spacing. See §5!

The goal here is to map the HI in the 3-d space of  $l, b, v$  (that’s Galactic longitude, latitude, and velocity) and then present the results in one or more color images.

### 13. MAPPING THE MAGELLANIC STREAM

The Magellanic Stream is an intergalactic tidal stream produced by gravitational interaction between the Magellanic Clouds and the Milky Way. The signal is weak ( $\sim$  a few tenths K), so you need to use much longer integration times than for the above projects—a minimum of 10 minutes per point. You need to map the pie-shaped area bounded roughly by ( $\ell = 60^\circ \rightarrow 110^\circ$ ),  $b = -90^\circ \rightarrow -30^\circ$ ). This is about 1250 square degrees and needs about 310 profiles at  $2^\circ$  spacing. See §5! Also, the LSR velocity of this gas ranges from roughly  $-400$  to  $-100$  km/s along its length, so you need frequency switch by a large enough interval!

The goal here is to map the HI in the 3-d space of  $l, b, v$  (that’s Galactic longitude, latitude, and velocity) and then present the results in one or more color images.

### 14. BASICS OF THE 21-CM LINE.

#### 14.1. Column Density and Mass

The 21-cm line, with frequency 1420.405751786 MHz, comes from atomic hydrogen (HI). In the terrestrial environment, H atoms quickly become  $H_2$  molecules; in interstellar space, where densities are far lower than in the best vacuum systems on Earth and there are “lots” of UV photons that dissociate  $H_2$ , H remains atomic unless it resides inside dark clouds where it is shielded from starlight.

The intensity of the 21-cm line is directly proportional to the column density of H atoms as long as the opacity of the line is small; this is a reasonably good approximation (but not perfect, particularly in the Galactic plane where the line is strong). With this approximation,

$$N_{HI} = 1.8 \times 10^{18} \int T_B(v) dv \text{ cm}^{-2}. \quad (2)$$

Here  $N_{HI}$  is the column density of H atoms—the number of atoms in a  $1 \text{ cm}^2$  column along the line of sight;  $T_B(v)$  is the brightness temperature of the 21-cm line, which is a function of velocity  $v$ ; and  $v$  is the velocity in  $\text{km s}^{-1}$ . The velocity  $v$  is produced by the Doppler effect, so a frequency shift  $\Delta\nu$  from line center corresponds to velocity  $v = -c \frac{\Delta\nu}{\nu}$  or, for the 21-cm line,  $v = -\frac{\Delta\nu}{4.73 \text{ kHz}}$  km/s. Note the minus sign! It means that positive velocities are receding—a very convenient convention for astronomy, because of the expansion of the Universe.

Note an important corollary to equation 2: If we consider a small velocity interval  $\Delta v$ , then

the number of H atoms in the column in that velocity range is just

$$N_{HI}(v \rightarrow v + \Delta v) = 1.8 \times 10^{18} T_B(v) \Delta v \text{ cm}^{-2} . \quad (3)$$

This is very important, because it gives us the opportunity to make maps of the interstellar gas at different velocities and to determine how it moves.

To get the column density we need to get the brightness temperature  $T_B$ , which is not the same as our antenna temperature  $T_A$ . The relationship between these depends on the relative size of the source and the beam. This is equation (9) in the “Fount of All Knowledge!” handout, namely

$$T_A \approx T_B \frac{\Omega_s}{\Omega_s + \Omega_b} , \quad (4)$$

where  $\Omega_s$  and  $\Omega_b$  are the solid angles of the source and beam, respectively. From this, we see that if the source fills the beam ( $\Omega_s \gtrsim \Omega_b$ ) then  $T_A \approx \langle T_B \rangle$  (the brackets denote the average over solid angle); while if it is much smaller ( $\Omega_s \ll \Omega_b$ ) then  $T_A \approx \frac{\langle T_B \Omega_s \rangle}{\Omega_b}$ , i.e.  $T_A$  is smaller by the ratio of the solid angles.

To get the mass of HI from the column density, you need to know the area of the region in *linear* measure, which is just  $\Omega d^2$ , where  $d$  is the distance. Each HI atom has mass  $m_H$ , so the total mass of HI in a region of size  $\Omega$  is just

$$M_{HI} = m_H d^2 \langle N_{HI} \Omega \rangle . \quad (5a)$$

Here  $\langle N_{HI} \Omega \rangle$  is shorthand for the general relation, which uses an integral:

$$\langle N_{HI} \Omega \rangle = \int_{\text{region}} N_{HI} d\Omega \quad (5b)$$

Substituting for  $N_{HI}$  from equation 3, we have

$$M_{HI}(v) = 1.8 \times 10^{18} \Delta v d^2 m_H \langle T_B \Omega \rangle \text{ gm} . \quad (6)$$

Units are cgs. Sometimes there is a well-defined source with boundaries; in this case, to get the mass of the whole source, we use the solid angle occupied by the source,  $\Omega_s$ .

Sometimes (in fact, often) we want to know the mass seen *by the telescope* for some particular observation. For an extended region with  $\Omega \gg \Omega_b$ ,  $T_A = T_B$  and the telescope sees the solid angle  $\Omega_b$ , so the product  $\langle T_B \Omega \rangle = T_A \Omega_b$  because angular area seen by the telescope is limited by its beam

size. In contrast, if the HI emission is limited to a small region—a small source with  $\Omega_s \ll \Omega_b$ —then  $T_A \approx \frac{\langle T_B \Omega_b \rangle}{\Omega_s}$  so the product  $\langle T_B \Omega_s \rangle = T_A \Omega_b$ ; the telescope sees the whole source.

For both extremes, the product  $T_B \Omega = T_A \Omega_b$ . It’s not only these two extremes, but for *all* sources the product  $\langle T_B \Omega \rangle = T_A \Omega_b$ . Thus, it is always true that the mass seen by the telescope is

$$M_{HI}(v) = 1.8 \times 10^{18} \Delta v \, d^2 \, m_H \, T_A \Omega_b \, \text{gm} . \quad (7)$$

The distance  $d$  is usually a function of velocity  $v$ , especially in the Galactic plane.

$T_A(v)$  is directly measured and  $\Omega_b$  is the telescope beam area, which is known, so it’s easy to calculate  $M_{HI}(v)$ —but only if you know the distance! Often you don’t know the distance, but you might have a hunch for a reasonable value for the distance. Suppose this is 100 parsecs. In this case, people usually evaluate the mass for this distance and, when giving the mass, say “The mass is  $xxx \times d_{100}^2$ , where  $d_{100}$  is the distance in units of 100 pc”.

## 14.2. Converting Galactic Rotation to Doppler Velocity

Measurement of the Doppler shift caused by differential Galactic rotation for  $0^\circ < \ell < 90^\circ$  allows a direct determination of the Galactic rotation curve inside the Solar circle, using the “tangent point” method. See Burton’s article “Structure of our Galaxy from Observations of HI” in *Galactic and Extragalactic Radio Astronomy, second edition* (editors: G.L. Verschuur and K.I. Kellermann). In essence, you use the following equation.

We won’t go through the derivation here; we cover it in class, and it is also done in Burton’s article, page 303-304. Let  $V_{Dopp}$  be the Doppler velocity (this is also the observed LSR velocity),  $V(R)$  be the Galactic rotation velocity at Galactocentric distance  $R$ , and let the subscript  $\odot$  denote values at the Solar circle. Then we have

$$V_{Dopp} = \left[ \frac{V(R)}{R} - \frac{V(R_\odot)}{R_\odot} \right] R_\odot \sin(\ell) \quad (8)$$

The values at the solar circle are  $V(R_\odot) \approx 220 \text{ km/s}$ ,  $R_\odot \approx 8.5 \text{ kpc}$ .

## 15. DISPLAYING YOUR DATA

Before actually working with images on the computer, you may need to familiarize yourself with our imaging handouts:

1. MAP PROJECTIONS: REPRESENTING A SPHERICAL SURFACE ON A COMPUTER SCREEN.
2. `jupyter_tutorials/lab4` has examples of making images, colorbars, and map projections.

## 15.1. MAP PROJECTIONS: REPRESENTING A SPHERICAL SURFACE ON A COMPUTER SCREEN

Computer screens consist of an array of dots that can glow in various colors. The dots are arranged in a square array and are called *pixels*. Images are the same, with the added feature that the pixels need not be square; that is, then horizontal distance can differ from the vertical one. To display our data as an image on the screen, we must populate these pixels with observed data.

Our observed positions do not lie on this grid. Rather, our observations lie on the celestial sphere. We need to represent this spherical surface on our 2d pixellated computer screen—or as a 2d image on a flat piece of paper. There are innumerable ways to do this *projection*, each of which has its own desirable properties. No projection is perfect; each is a compromise among various desirable and undesirable properties.

Our handout MAP PROJECTIONS describes the most common projections. Two examples:

1. The simplest is the *cylindrical equidistant projection*, for which the entire sky is represented by longitude horizontally and latitude vertically with square pixels each having the same size in  $(\Delta\ell, \Delta b)$ . Near the equator this is a very nice projection because it has many desirable qualities: it is nearly conformal, the pixels are nearly of equal solid angle. But as you move away from the equator, these properties decay with increasing severity because of foreshortening.
2. Suppose we want to be as conformal as possible, particularly with respect to representing small circles (supernova remnants or supershell walls). This is the *stereographic projection*, which is centered on its own defined pole and for which the conversion between its  $(long, lat)$  and the pixel values  $(x, y)$  is

$$R = \tan[0.5 \times (90. - lat)] \quad (9a)$$

$$x = R \cos(long) \quad (9b)$$

$$y = R \sin(long) \quad (9c)$$

You can use the procedures we developed to create a stereographic or gnomonic projection; see our ‘How to create a perspective projection’ on the web page. It tells how to define a new coordinate system by specifying the pole of the projection, which ideally is near the center of the supershell being mapped, how to convert  $(ra, dec)$  or  $(\ell, b)$  to the  $(long, lat)$  of that new system, and how to populate the projection map plane.

## 15.2. Regridding

How do we populate this  $(x, y)$  grid with our data? This process is called *regridding*. There are several ways to regrid; we describe the one that loses least information (but requires the most computer resources—our philosophy is ‘computers are cheap’).

To regrid proceed as follows:

1. Set the angular  $(x, y)$  pixel size. The size must be smaller than the smallest great-circle distance between observed points. For example, if the separation between observed points is 2 degrees, a pixel size of 1 degree (or 0.1 degree) is OK. For the cylindrical equidistant projection with a pixel size of 1 degree there are 360 horizontal pixels and 180 vertical ones, for a total of 64800 pixels.
2. Create an empty 3-d data cube of the appropriate dimensions. The first two dimensions are  $(x, y)$  and the third is velocity. If you have 256 velocity channels, the above cylindrical equidistant cube would have dimensions  $360 \times 180 \times 256$ . The cells in this cube are 3-d and are called *voxels*.
3. For each pixel, find the nearest observed position. For the angles on the sky, a suitable approximation for the distance squared is  $[(\cos(b)\Delta\ell)^2 + \Delta b^2]$ . Populate that pixel with the nearest observed data value. For the velocity, use linear interpolation. (`scipy.interpolate` has many convenient options for this purpose).

### 15.3. Displaying Your Data—The Exploratory Phase

For public presentation, you may want to display your data cube in its full 3d glory with a 2d image where brightness represents ‘amount’ (e.g., the integrated area of the HI line) and color the mean velocity. Or by describing each pixel by 3 numbers (e.g., the integrated intensity within 3 different velocity ranges) and writing them on the same image plane as the 3 independent colors red, green, blue.

However, making effective use of color requires defining what color means. Set up an `matplotlib` imaging window and look at successive  $(x, y)$  scalar images at different velocities. That is, make a ‘movie’. For our above example  $360 \times 180 \times 256$  data cube, a quick and dirty way is:

```
plt.ion() # makes pylab interactive, so you can replot data in the same figure
fig = plt.imshow(data[...,0], vmax=max, vmin=min, cmap=cmap)
plt.draw() # not necessary if run within IPython
for i in xrange(1, data.shape[-1]):
    time.sleep(1) # change data every 1 second
    fig.set_data(data[...,i])
    plt.draw()
```

Here, colors are chosen from the `cmap` (there are bazillions of options). The keywords (`min`, `max`) mean a data value of `min` gives the minimum color and `max` gives the maximum.