Milky Way Blues
A more detailed explanation

In galaxies, the space between the stars is filled with gas and dust. This interstellar medium spans a range of gas phases (neutral atomic, neutral molecular, ionized), densities and temperatures. Astronomers investigate each phase with spectroscopy of atomic and molecular emission lines, which provide valuable information on the gas motions. A spectrum measures the brightness of the emission line as a function of frequency or wavelength. But frequency or wavelength can be converted to velocity based on the Doppler Effect in which the wavelength measured by the observer is shifted depending on whether the radiating object is approaching or receding. Figure 1 shows two spectra from the atomic and molecular gas components of the Galaxy in which the intensity of the line emission varies with velocity derived from the Doppler Effect. But what causes these velocity shifts?

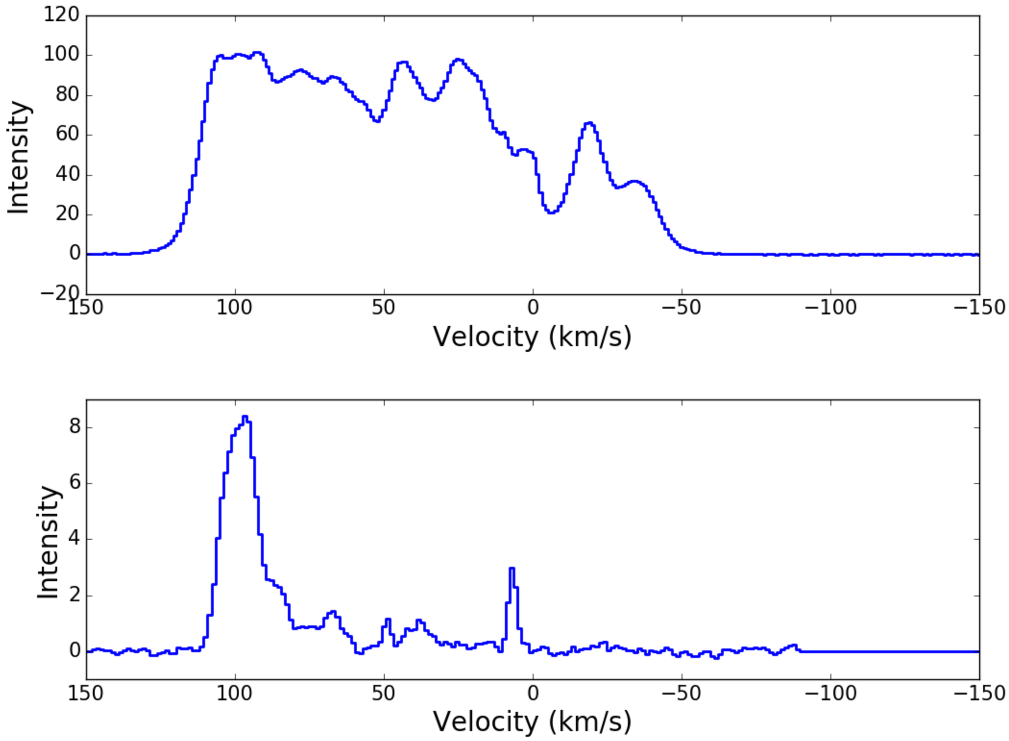

Figure 1 - (top) Spectrum of the neutral atomic hydrogen line at a rest wavelength of 21 cm. (bottom) Spectrum of Carbon Monoxide (CO) at a rest wavelength of 0.26 cm at the same position. CO is the primary tracer of molecular hydrogen. Since molecular gas is not as broadly distributed in the Galaxy as atomic gas, the emission occurs over more limited velocity intervals.

The largest velocity shifts arise from the orbital motion of gas around the center of the Galaxy. Other processes that can influence the gas motions at smaller levels include the gravitational effects of spiral arms, stellar winds from massive stars, and turbulence, which introduces a random component.

In the Milky Way, a single spectrum observed at a given position can simultaneously measure the gas velocity at various distances from the center of the Galaxy (Figure 2). Emitting elements along the line of sight (green solid circles) produce the observed intensity bumps in the spectra at the corresponding Doppler velocities. The Doppler velocity at each intensity bump is the *difference* between the velocity of the emitting gas that is projected along the line of sight and the Sun's velocity projected along this same line of sight. For circular orbital motions, the measured Doppler velocities depend on the distance from the Sun, the line of sight through the Galaxy, and the Galactic radius of the emitting gas relative to the radius of the Sun. For example, on the left side plot in Figure 2 for the line of sight to the left of the vertical line, the Doppler velocities are redshifted for positions within the Solar circle (dotted line). The largest redshifted velocity occurs at the point lying on a circle (dashed line) whose tangent coincides with the line of sight. Along this same line, the velocities are blue shifted for positions outside of the Solar circle. This pattern of Doppler velocities is reversed for the line of sight to the right of the vertical line. For positions along the Solar circle, the projected motions of the gas and the Sun cancel and the Doppler velocity is zero. For the outer Galaxy directions (right), the Doppler velocities are either all blue shifted or redshifted depending on whether the line of sight is left or right of the vertical line.

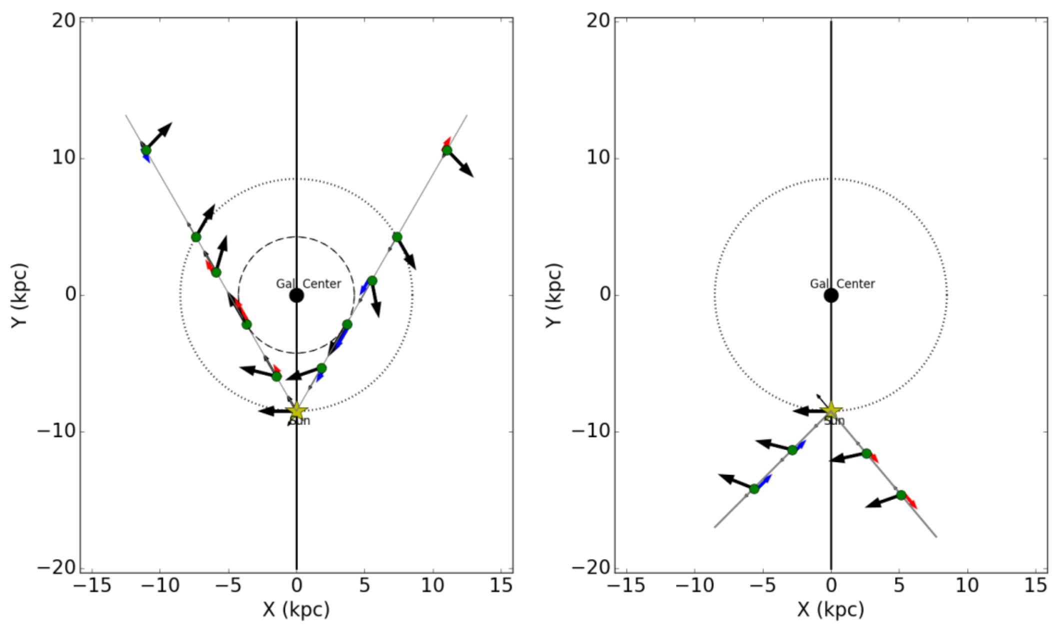

Figure 2 - A schematic view of the Galaxy with lines of sight directed towards the inner Galaxy (left) and outer Galaxy (right). A spectrum along a line of sight (grey lines), samples gas at different radii from the Galactic Center and distances from the Sun. Circular orbital motions (black arrows) around the center of the Galaxy are assumed. The narrow black arrows show the projection of the orbital motions along the line of sight. The Doppler velocity is represented as the direction and color of the blue (approaching) and red (receding) arrows. No blue or red arrow means the Doppler velocity is zero.

It is the variation of velocities along the line of sight and at different directions that can be transformed into a sequence of musical pitches.
The algorithm that transforms the spectra into musical notes requires a set of parameters that modify the character of the sound. A key parameter is the velocity interval that defines a musical octave. Once this interval is set, the spectral information can be transformed into a musical scale and generate a one-to-one map between velocity and musical pitch as shown in Figure 3. This step provides tonality to the spectrum and establishes a harmonic relationship to a sequence of notes.

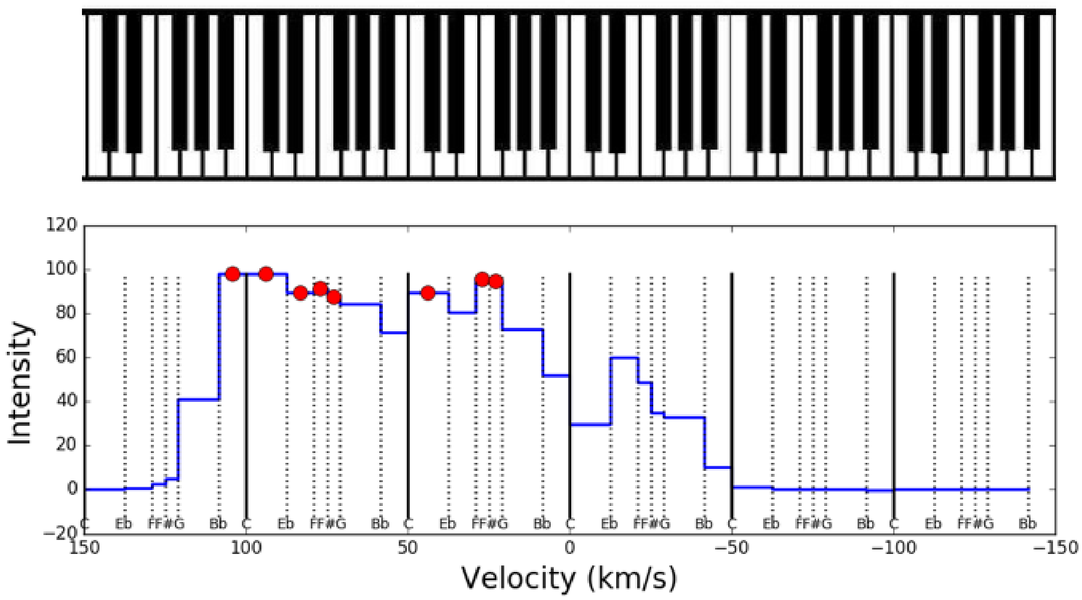

Figure 3 The atomic gas spectrum from Figure 1 rescaled to a pentatonic minor blues scale in the key of C below a corresponding keyboard covering the same 6 octaves where one octave spans *50 km/s. The notes in each octave are shown at the bottom. The red circles show the 8 brightest spectral channels, which are selected as the notes to play in this musical bar.*

We have taken the data from the several radio spectroscopic surveys of the Milky Way to construct a short musical composition that demonstrates the algorithm. These data include the 21 cm line of atomic hydrogen (Kalberla *et al.* 2005), the millimeter line of Carbon Monoxide as a proxy to molecular hydrogen (Dame *et al*. 2001), and hydrogen recombination lines that trace ionized gas (Anderson *et al.* 2011). Each data set is assigned an instrument. The atomic gas information is played by the acoustic bass and the ionized gas is expressed as a baritone saxophone. The wood blocks and piano parts are both based on the molecular gas but are composed with different input parameters. For this demonstration, the velocities with the brightest intensities in the transformed spectrum are selected and turned into pitches. The sequence and duration of a note are set by its intensity relative to the other selected notes in the spectrum. The notes for a given direction are distributed over a single measure or bar.

In the visualization, each line represents a set of data and shows the direction in the Galaxy at which the telescope was pointing when observing the spectra. These respective lines swing around the Galaxy from the position of the Sun with different angular increments. For the bass (atomic) and wood blocks (molecular), these lines sample the same directions in time and therefore, move together. The positions of the circles along these lines represent the locations in the Galaxy that correspond to the selected velocities and notes to be played. The size of each circle denotes the duration of the note. The colors that fill the circles indicate whether the motions are approaching (blue) or receding (red). Darker shadings imply larger Doppler shifts.

When listening to the composition for the first time, it is useful to follow pitch changes of a single instrument as these lines sweep through different sectors of the Galaxy. The saxophone and piano are played with higher volume and are easier to follow. One can hear low or high pitches depending on the direction of the line and whether the note location along the line is inside or outside of the Sun's radius as shown in Figure 2. The changes of pitch from one sector to another arise from the rotation of the Galaxy. Any melodic phrase emerges naturally from this orbital motion and simple rules on selecting, sequencing, and setting durations of notes extracted from the spectra. This musical expression of measured velocities allows one to hear the rotation of the Milky Way.

References

Anderson, L. D., Bania, T. M., Balser, D. S., Rood, R. T. Astrophysical Journal Supplement, 194, 32 (2001)

Dame, T.M., Hartmann, Dap, Thaddeus, P. Astrophysical Journal, 547, 792 (2001)

Kalberla, P. M. W., Burton, W. B., Hartmann, Dap, Arnal, E. M., Bajaja, E., Morras, R., Poppel, W. G. L. Astronomy and Astrophysics, 440, 775, (2005)