THE VATLY RADIO TELESCOPE

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Abstract: A 2.6 m radio telescope, tuned on the 21 cm atomic hydrogen line, has been installed on the roof of the VATLY laboratory in Ha Noi. After a brief description of its performance, I report on measurements of the power density spectrum made over the visible part of the Milky Way disk. The data give strong evidence for differential rotation of the Galaxy with respect to the Sun and for an important clumping of molecular hydrogen in distinct clouds. The analysis of the measured Doppler spectra is used to map atomic hydrogen over the disk of the Galaxy. The result is compared with the arm structure observed at visible and infrared wavelengths.

Keywords: *radio astronomy, 21cm hydrogen line, Milky Way, Sun*

1. THE VATLY RADIO TELESCOPE

In April 2011, a small radio telescope (SRT) has been installed on the roof of the VATLY astrophysics laboratory, commissioned and run-in. It is now routinely taking data.

Figure 1. *Close-up views of the SRT antenna and of the motor system (gear box and telescopic arm, left panel) and of the feed horn and the calibration antenna (right panel).*

The telescope is equipped with a mobile parabolic dish, 2.6 m in diameter, remotely adjustable in elevation and azimuth (Figure 1). It is developed for observation of frequencies in the region of the 21 cm hydrogen line

The reflected power is collected at the focus, where it is locally preamplified, shifted to lower frequency using standard superheterodyne, amplified and digitized. Standard data collection consists in a sequence of successive measurements of ~7.7s duration each, digitized in the form of a frequency histogram covering ~1.2 MHz in 156 bins of ~7.8 kHz each. The hydrogen line signals the presence of hydrogen clouds in the field of view and is associated with electron spin flip in the hydrogen atom. Galaxies such as ours contain many such clouds and the signal from the Milky Way is particularly strong. On the contrary, the continuum signals the presence of ionized matter and is associated with thermal or “free-free” (bremsstrahlung) emission.

2. THE SUN: POINTING ACCURACY

The Sun gives a strong signal in the continuum while the 21 cm line is essentially unaffected. As its apparent diameter is much smaller than the antenna lobe (the Sun seen at 21 cm is dominated by solar spots above a disk having the same size as the photosphere) the Sun can be considered as being a point source. In this work we use it to assess the SRT pointing accuracy. Two methods are used: grid scans (25 measurements on a grid centered on the Sun, takes only 6 minutes) and drift scans (1 hour measurement at a fixed point where the Sun passes after 30 minutes; locates the SRT on a line, several measurements are necessary). Ultimately, we obtain corrections of ~1^{o}, and accuracies of ~0.3^{o}. The size of the lobe (FWHM), as obtained from the drift and grid scans (their results are in excellent agreement), has been measured to be 5.5±0.3^{o}, corresponding to $\sigma=2.3\pm0.1^{o}$.

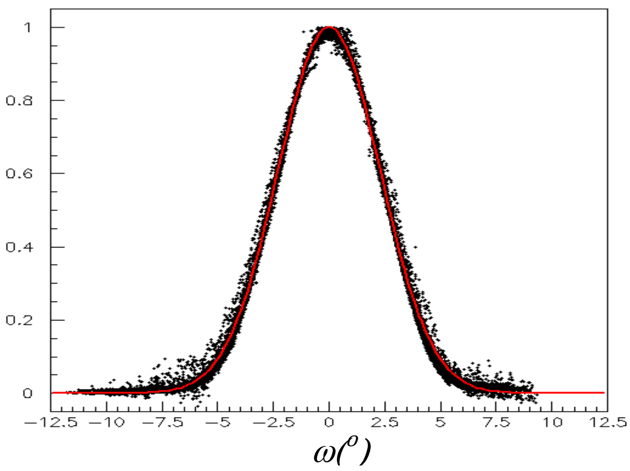

Figure 2. *Dependence of the amplitude of the Sun signal on the angular separation between Sun and SRT. The best Gaussian fit is shown as a line.*

3. THE 21 CM MAP: EVIDENCE FOR ROTATION

3. 1 Observations

A set of 117 spectra have been recorded by scanning the visible part of the disk of the Milky Way. The galactic longitude was chosen in steps of 2.5^{o} from –20^{o} to 270^{o}. Pointing corrections as defined in Section 2 were systematically applied. A typical spectrum is shown in Figure 3 (left).

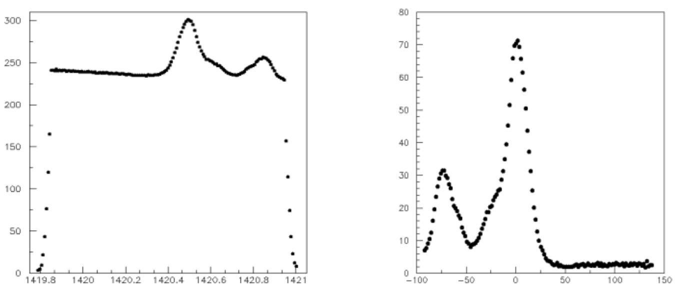

Figure 3. *A typical spectrum at 70^{o} galactic longitude. The received signal is shown as a function of frequency (MHz) on the left panel and as a function of velocity (km/s), after continuum subtraction, on the right panel.*

On each spectrum, a constant continuum has been subtracted and the peculiar and rotational movement of Sun (v_{sun}) has been removed. Conversion of the frequency scale *(f)* into a velocity scale *(v)* was made using the Doppler formula:

$$v=c(f_0-f)/f_0-v_{sun}$$

where c is the light velocity and f_0 the central frequency of 1.42 GHz. Figure 3 (right) shows the result in the case of the raw spectrum displayed in Figure 3 (left).

3. 2 Evidence for differential rotation

The Galaxy rotation curve is reasonably well known at galactic radii smaller than that of the Sun: we use the form defined in [1] from HI accurate measurements, illustrated in Figure 4. From the Sun outward, we take a quadratic dependence on radius of the form $v(r)=v_{sun}(1+0.1(5-r/r_{sun})(r/r_{sun}-1))$ where $r_{sun}=8.4$ *kpc* and $v_{sun}=220$ *km/s*. It reaches its maximum at $3r_{sun}$, beyond which it is assumed to remain constant.

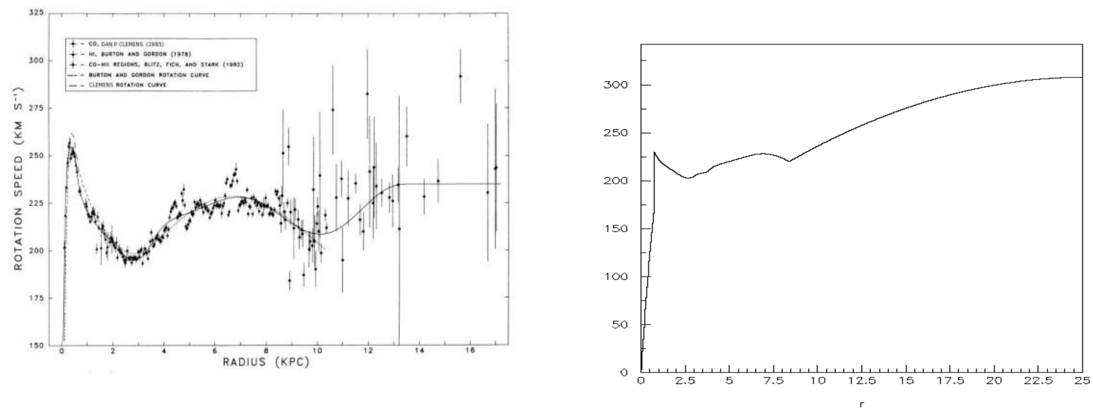

Figure 4. *Rotation curve from [1]. Data are HI for radii smaller than r_{sun} and CO for radii larger than r_{sun}. The right panel displays the rotation curve used in the present work.*

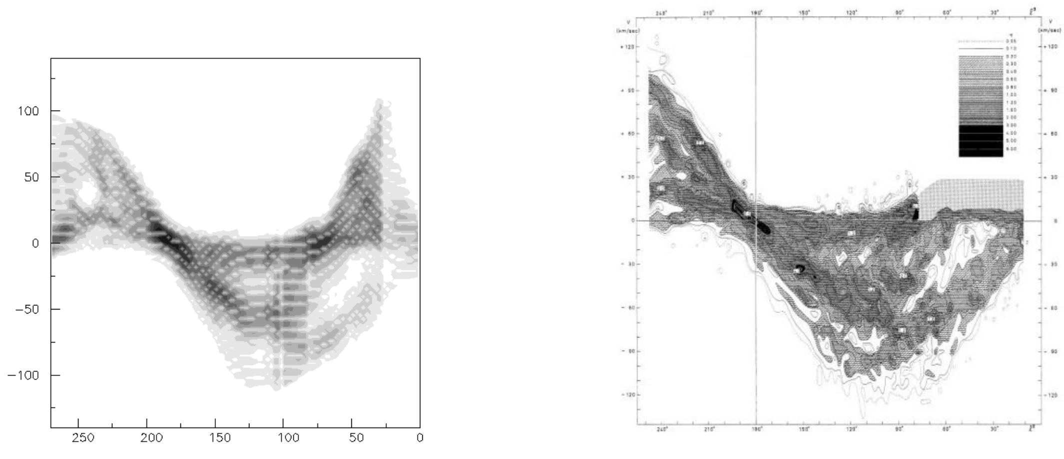

Figure 5. *Distributions in the (φ,v) plane, units are degrees and km/s. Left panel: present measurements; right panel: measurements from [2].*

Figure 5 (left) displays our measurements in the (φ,v) plane where v is the measured radial velocity and $\varphi=2\pi-l$, l being the galactic longitude. It is compared in Figure 5 (right) with other measurements [2]. The observed sine wave is very strong evidence for a global differential rotation of the Galaxy.

4. MAPPING THE HI CLOUDS

4.1. The problem

Once the velocity spectrum is known for a given line of sight, it should be straightforward, by using the rotation curve, to calculate the position of the HI cloud along the line of sight, at a distance d from the Sun. Indeed, as can be seen from Figure 6,

$$v = V(rcloud)sin(\theta - \varphi) \text{ and } r_{cloud}/sin\varphi = r_{Sun}/sin(\theta - \varphi) = dsin\theta$$

Here, r_{Sun}, the distance of the Sun to the centre of the Galaxy, is known; v and φ are measured; the function V (the rotation curve relative to the Sun rotation), is known. One is left with three unknowns (d, θ and r_{cloud}) and three equations. However, as is obvious from Figure 6, changing θ into $\pi - \theta + 2\varphi$ and d into $d - 2r_{cloud}cos(\theta - \varphi)$ gives another solution, marked "ghost" in the figure. In the case illustrated, where $r_{cloud} < r_{Sun}$, there are indeed two possible solutions and the position of the cloud cannot be measured unambiguously. On the contrary, when $r_{cloud} > r_{Sun}$, there is only one solution, the ghost being now at opposite direction from the line of sight. In principle, all what is needed in order to obtain the HI map is to solve the above equations for each peak of the observed spectra. In practice one has to face the ambiguity problem just mentioned.

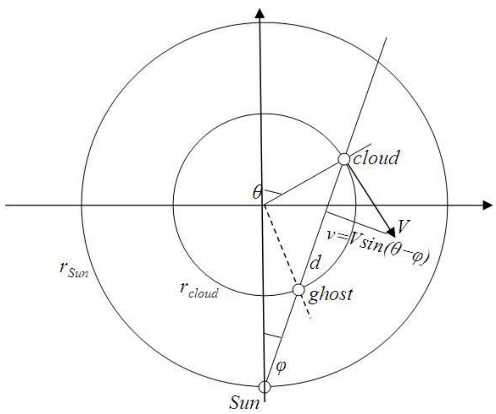

Figure 6. Geometry of the cloud mapping problem.
The configuration shown here is such that $r_{cloud} < r_{Sun}$.

4.2 First approximation of the cloud map

Each spectrum was individually inspected and resolved into a series of peaks and one peak corresponds to one or two possible clouds. For each peak, one then defines a d interval on the line of sight, within which the HI source needs to be confined in order to contribute to the peak. In ambiguous cases, two such intervals are defined. The resulting map is shown in Figure 7. A clear arm structure, resulting from the continuity of the peak configuration between neighbour sectors of galactic longitude, is visible.

Two clouds of same absolute luminosity located at different distances on the line of sight have different apparent luminosities. To take this effect into account, an additional weighting factor must be applied, equal to $(d/r_{Sun})^2$. The right panel of Figure 7 compares the result, using such a weight, with the known arm structure [3].

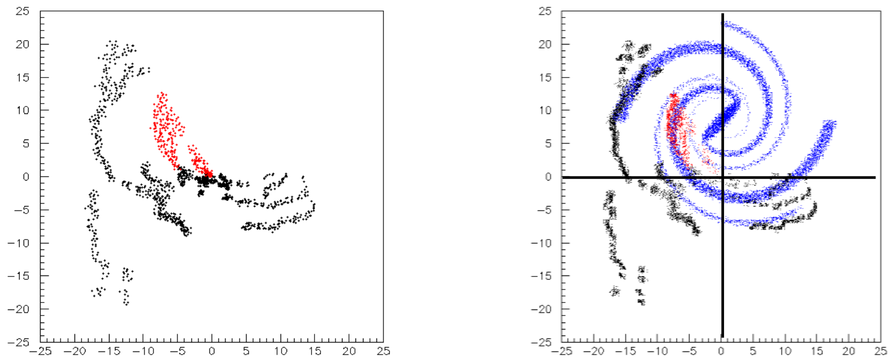

Figure 7. *First approximation maps obtained at galactic longitudes between 30° and 270°. Red dots mark ambiguous sources. On the right panel the known arm structure (blue) has been superimposed.*

4.3 Cleaning the map

The non ambiguous cases provide a direct mapping of the measured signal onto the galactic disk: to each velocity bin is associated a unique distance bin in the galactic longitude interval being considered. Figure 8 displays such a map, using weights $(d/r_{Sun})^2$. It is remarkable that the small peak that was causing the narrow cloud distribution in the [90°,180°] galactic longitude quadrant at large distances is now diluted in a broad continuum.

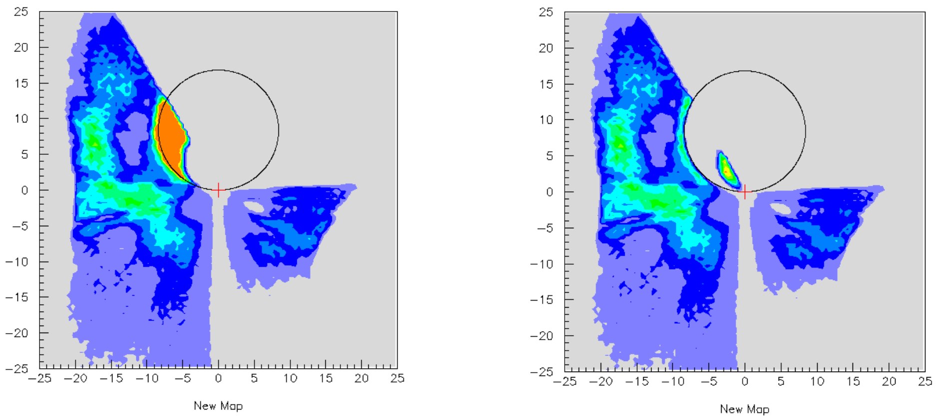

Figure 8. *Measured HI map of the Milky Way disk using weights $(d/r_{Sun})^2$. The circle centred on the centre of the Galaxy and passing by the Sun is shown in black. Its inside is associated with ambiguous cases, its outside with non-ambiguous cases. Ambiguous cases are displayed separately in the two panels, the far-away solution in the left panel and the closer solution in the right panel.*

The ambiguous cases give two possible distances for each velocity bin. The farther away solution is displayed in the left panel of Figure 8 and the closer solution in the right panel. The choice between the two is somewhat arbitrary and cannot be done with certainty. However, we note some arguments of relevance to such a choice:

− The far-away solution is disfavoured as giving an outstandingly large HI density in comparison with the rest of the disk.

− The known arm structure, however, tends to favour the far-away solution as is apparent from the right panel of Figure 8.

− It may well be that the real cloud distribution is a mixture of the two solutions.

5. SUMMARY

We have given evidence for the excellent performance of the VATLY 2.6 m radio telescope, tuned on the 21 cm atomic hydrogen line, with a pointing accuracy of ~0.3^{o}. . Measurements of the power density spectrum made over the visible part of the Milky Way disk have provided strong evidence for differential rotation of the Galaxy with respect to the Sun and for an important clumping of molecular hydrogen in distinct clouds. The analysis of the measured Doppler spectra has been used to map atomic hydrogen over the disk of the Galaxy. The result supports the arm structure observed at visible and infrared wavelengths.

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