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A high sensitivity HI survey of the sky at $\delta \leq -25^\circ$

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Abstract. This paper reports on a high sensitivity λ 21-cm neutral hydrogen survey of the sky south of $\delta \leq -25^\circ$. A total of 50980 positions lying on a galactic coordinate grid with points spaced by $(\triangle l, \triangle b) = (0\overset{\circ}{.}5/\cos\ b,\ 0\overset{\circ}{.}5)$, were observed with the 30 m dish of the Instituto Argentino de Radioastronomía (IAR). The angular resolution of the survey is HPBW = 30′, and the velocity coverage spans the interval -450 km s^{-1} to $+400$ km s^{-1} (LSR). The velocity resolution is 1.27 km s^{-1} and the final rms noise of the entire database is $\sim$ 0.07 K. The brightness temperature scale is accurate to 5%.

Key words: surveys — ISM: general — Galaxy: general radio lines: ISM — ISM: clouds

1. Introduction

The neutral hydrogen atom (HI) is the most abundant of the atomic constituents known to exist in the interstellar medium (ISM). Its hyperfine transition at λ ~21-cm (ν = 1420.40576 MHz), predicted on theoretical grounds by Dutch astronomers (van de Hulst 1945), was first successfully detected by an American team (Ewen & Purcell 1951). Shortly afterwards, this line was also observed by Dutch (Muller & Oort 1951) and Australian (Pawsey 1951) groups, respectively.

Taking into consideration the excitation conditions prevailing in the ISM it was realized (van de Hulst et al. 1954; Purcell & Field 1956; Field 1958), that this line could be a powerful tool to directly explore the structure of the Milky Way at large. Indeed, the λ ~21-cm emission is so ubiquitous that its brightness temperature, column density and velocity field provide key information on a variety of physical circumstances which can be found in the ISM. Furthermore, for a few phenomena, like for most of the high velocity clouds (HVC), the 21-cm line remains the only tracer as yet identified.

Therefore, it is understandable that right from the beginning a lot of effort went into carrying out surveys of the HI 21-cm emission line, which cover huge areas of the sky, with a sensitivity good enough to be suitable for general investigations of the galactic interstellar medium (ISM). The main characteristics of the major southern sky HI surveys are summarized in Table 1. Bearing in mind their limitations in sensitivity, velocity resolution and both velocity and spatial coverage, and considering that the present day technology of spectral analyzers and low noise receivers allows a much better velocity coverage and resolution, as well as a much lower rms noise, it was highly desirable to undertake a long-term observational project with the aim of surmounting the restrictions inherent to the available HI surveys.

From the beginning it was clear that to succeed in this undertaking, the observing instrument should meet two main requirements, namely: a) a system temperature against cold sky in the range of $30-40$ K, and b) a back-end that should be able to provide both a large velocity coverage, at least 1000 km s^{-1}, and a velocity resolution of the order of 1 km s^{-1}. As a back-end we ended using the "old" Arecibo 1008-lags autocorrelator, which, at that time, by mid 87, had already been replaced by a new one. The computer controlling "on-line" the data-taking process was a μVAX II. Since the autocorrelator interfaces and the driving program were originally written for a Harris Computer, we had to rebuild the hardware interfaces and rewrite the data-taking software. As for the receiver a dual polarization L-band cooled receiver was built by a IAR staff member at the Max-Planck-Institut für Radioastronomie (MPIfR), Bonn, Germany, with the technical support of their radio-frequency laboratory, which

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Table 1. Relevant parameters of the southern HI surveys

Survey	HPBW (′)	rms noise (K)	Velocity coverage ($\mathrm{km\,s^{-1}}$)	Velocity resolution ($\mathrm{km\,s^{-1}}$)	Grid spacing (degrees)	Region surveyed
Cleary et al. (1979)						$\delta \leq -30°$
Intermediate latitude	48	0.3	$-148 \leq V \leq +300$	7	$\triangle\delta = 1$	$\mid b \mid \geq 10°$ $b \geq -25°$
High latitude	48	0.3	$-230 \leq V \leq +218$	7	$\triangle\delta = 2$	$\delta \leq -30°$ $b < -25°$
Kerr et al. (1986)	48	0.3	$-150 \leq V \leq +150$	2.1	$\triangle l = 0.5$ $\triangle b = 0.25$	$240° < l < 350°$ $\mid b \mid \leq 10°$
Colomb et al. (1980)	30	0.8	$-50 \leq V \leq +50$	2	$\triangle\delta = 1.0$	$\delta \leq -25°$ $\mid b \mid \geq 10°$
This Survey	30	0.07	$-450 \leq V \leq +400$	1.27	$\triangle l = 0.5/\cos b$ $\triangle b = 0.5$	$\delta \leq -25°$

was at that time developing a similar receiver for the 100-m Effelsberg radiotelescope. The details of the autocorrelator hardware and software, and the automation of the antenna movements will be published elsewhere.

An extra motivation was brought into scene, when we became aware of the characteristics of the northern hemisphere Leiden/Dwingeloo HI survey (Hartmann 1994; Hartmann & Burton 1997). The observational parameters intended for this survey (see Table 1) were so similar to the one we were planning to use, that the idea of having, as a result of both projects, a whole sky high sensitivity HI survey of uniform spatial coverage, derived naturally in an agreement with Drs. Burton and Hartmann. What we describe here is the IAR survey itself and its principal merits, as compared to the others listed in Table 1. These merits lie in the improved sensitivity, which is a factor of four to ten better, the sky coverage, the sampling, and in the fact that it will be corrected for the effects of stray radiation.

2. Observations

The observations were made with the 30 m-dish of the Instituto Argentino de Radioastronomía (IAR). They were started on June 1994 and it took nearly 3.5 years to complete the data acquisition phase. The half power beam width (HPBW) and the main beam efficiency at 21-cm are $30'$ and ~ 0.7, respectively. The movements of the dish, (equatorial mounting) due to constructive constraints, are limited to $-90° \leq \delta \leq -9\overset{\circ}{.}1$, and $\pm 30°$ from the local meridian. The dual-channel front-end consisted of helium-cooled HEM amplifiers with a noise temperature of $\sim$20 K. The total system temperature against cold sky was about 35 K. The backend spectral line analyzer was the former 1008-channel autocorrelator from the Arecibo Observatory (at present at the IAR on a long term loan basis), in its 1.6 bits sampling mode. A bandwidth of 5 MHz was used throughout the observations, yielding a velocity separation of 1.05 $\mathrm{km\,s^{-1}}$ and a velocity resolution of 1.27 $\mathrm{km\,s^{-1}}$. These figures are similar to those of the Leiden/Dwingeloo survey, namely 1.03 and 1.25 $\mathrm{km\,s^{-1}}$, respectively. The total spectrometer velocity coverage was thus $\sim$1056 $\mathrm{km\,s^{-1}}$, centered at the radial velocity $V = 0$ $\mathrm{km\,s^{-1}}$. In this way, besides covering the entire velocity range expected from the overall galactic HI-emission, all but the most extreme HVCs, and the HI emission arising from the Magellanic System, were also observed. After the final data reduction, the effective velocity range covered by the survey is -450 $\mathrm{km\,s^{-1}} \leq V \leq +400$ $\mathrm{km\,s^{-1}}$, since channels close to the edges of the bandpass had to be dropped due to the effects of the filter that was used to set the bandpass. All radial velocities in this paper are referred to the Local Standard of Rest (LSR).

A total of 50980 different sky positions were observed in this work. In order to carry out the actual data taking, the sky area to be surveyed, with the only exception of the southern galactic pole cap, was divided in 2012 square cells $2\overset{\circ}{.}5$ in size. Each of these cells consisted of 25 positions. The remaining 680 positions were observed in 83 additional cells, containing each a varying number of points. The reasons for these grouping are tied to the limitations in the tracking capability of the antenna mentioned above and to the integration time. Since the total system temperature changes with galactic direction due to the different galactic background contributions, the integration time per position was chosen in order to reach our target rms noise of $\sim$ 70 mK. Typically, at high latitudes the integration time was of the order of 210 seconds, while at low latitudes it was about 270 seconds. The so-called total power observing mode, in its Standard Bonn Method flavour (Allen & Shostak 1979) was used to perform the observations.

Before undertaking the survey data taking phase, a program to determine the telescope pointing correction was performed (Morras & Bajaja 1994). The resulting pointing corrections were incorporated to the observing system. The overall pointing accuracy of the antenna was within $\pm 2'$ ($\leq$HPBW/15), for wind speeds lower than $\sim$3 m s^{-1}. Our adopted brightness temperature scale is tied to the point S9 ($l = 356.^\circ 00$, $b = -4.^\circ 00$) recommended as one of the standard fields by the IAU (van Woerden 1970). Due to the restrictions in the source tracking, we have defined a series of secondary HI calibrators. These points, whose main characteristics are given in Table 2, were chosen in such a way that two of them were always within the telescope horizon (Morras & Cappa 1995). The errors quoted in column six of Table 2, correspond to the rms value of the mean of individual measurements. In addition, a study of the HI-distribution across our prime calibrator, region S9 (or point IAR0 in our nomenclature), was carried out. Neutral hydrogen profiles were observed every $0.^\circ 25$ (in both l and b), over a square area of $2.^\circ 0$, centered on the calibration point. Williams (1973) obtained a value of 953 $\pm$ 71 K km s^{-1} for the integral of the brightness temperature at S9 over the velocity range -1.05 to $+14.75$ km s^{-1}. Since the beam of the Hat-Creek telescope (HPBW$\sim$35$'$) was slightly larger than ours (HPBW$\sim$30$'$), the IAR observations were smoothed down in order to match the angular resolution of Williams' observations. In this way the ratio of the brightness temperature scales was found to be $I_{\rm Hat-Creek}$(S9)/ $I_{\rm IAR}$(S9) = 1.023. Hence, the brightness temperature scale of the IAR observations was defined in such a way as to match a mean value of 932 K km s^{-1} for the mentioned integral.

Regarding our "brightness temperature scale", a word of caution is necessary. Indeed, to obtain a telescope independent birghtness temperature scale (Kalberla et al. 1982) stray radiation contamination should be removed first from the calibration points observed throughout the survey. Since this has not been done yet, the figures given in Table 2, in columns fourth and sixth, may be slightly in error.

Furthermore, five cold points distributed all over the observable sky and having a very low HI emissivity, were also selected (see Table 3). Their main purpose was to estimate the stray radiation from the sidelobes which enter the cold point profiles at different LSR velocities during the observation years. This correction is expected to be applied to the entire database by Kalberla & Hartmann (1999) using a model for the antenna pattern. The procedure will be similar to the one applied to the northern HI survey. (Hartmann & Burton 1997) with the advantage that for the construction of the model, a whole sky HI survey is now available. The modelling will be facilitated also by the equatorial mounting of the IAR dish which means that the orientation of the antenna pattern, with respect to the sky, is constant. We cannot specify in advance the effects of the stray radiation in our spectra. We can only estimate these effects on the basis of the results of the application of the correction to the northern survey which have been described in the above mentioned paper. From these results we may say that the most important effect is produced by the near sidelobes (NSL) which amounts to about of 10 to 15% of the observed intensity with a spectral distribution similar to the one produced by the main beam. The far sidelobes (FSL) add signals much more attenuated and with a spectral distribution generally not related to the main one. The effect of the FSL will be noticeable mainly far from the galactic plane, in regions where the HI signal is relativity weak.

It is worth mentioning that since our telescope never goes below an elevation of 35°, the extinction caused by the atmospheric air-mass column traversed by the 21-cm radiation before reaching the telescope, has been neglected. Usually, during a typical observing session several of our programm cells were observed. Right before and after a given cell was observed, a calibration point and a reference spectrum, to estimate the shape of the bandpass, were taken. The latter was observed by shifting the central velocity of the signal-band by $+1000$ km s^{-1}. Due to the stability of the overall system parameters, all reference spectra of a given session were averaged, producing a new interference-free high S/N reference spectrum, before carrying out the actual data reduction. The latter comprises the following main steps:

1. The mean reference spectrum of a given session was subtracted from every individual HI profile observed within a given program cell;
2. When present, interferences and faulty channels were removed from the output profile obtained in the previous step. Since many spectra were contaminated by spurious signals, most of them arising from man-made interferences and our local network of PCs, special care was taken in their removal. Most of the times the offending signal was a narrow spike only a few channels wide, but in some cases the interference was so strong that the entire HI profile was damaged beyond recovery. In this case, the corrupted spectrum was dropped from the observed cell and reobserved;
3. By fitting a polynomial to those regions of the HI profile judged to be free of line emission, the instrumental baseline was removed. Admittedly, the baseline–fitting proved to be the most difficult and time consuming aspect of the data reduction procedure. The degree of

Table 2. Calibration points for the IAR survey

Point	Gal. Long.	Gal. lat.	Peak T_b (K)	Peak Velocity ($\mathrm{km\,s^{-1}}$)	Prof. area ($\mathrm{K\,km\,s^{-1}}$)	Vel. range ($\mathrm{km\,s^{-1}}$)
IAR0(≡S9)	356.°00	−4.°00	84.2 ± 1.0	+5.2	932	−1.5 to +15.2
IAR1	4.°00	−25.°00	44.4 ± 0.6	+6.3	287.6 ± 3.2	+0.5 to +12.0
IAR2	304.°55	−28.°87	41.1 ± 0.3	+2.1	282.6 ± 3.9	−3.6 to +7.8
IAR3	304.°65	−33.°23	46.9 ± 0.4	+3.1	288.4 ± 5.3	−2.6 to +8.9
IAR4	298.°56	−37.°75	40.6 ± 0.5	+2.1	266.8 ± 3.8	−3.6 to +7.8
IAR5	301.°32	−28.°73	33.4 ± 0.6	+1.0	270.5 ± 3.2	−4.7 to +6.8
IAR6	219.°50	−12.°00	80.9 ± 0.7	+4.2	648.9 ± 5.9	−1.5 to +9.9
IAR7	247.°00	+17.°00	64.2 ± 0.7	−3.1	481.5 ± 5.5	−8.9 to +2.6
IAR8	290.°00	+5.°00	64.3 ± 0.6	−10.5	665.7 ± 6.0	−16.2 to −4.7
IAR9	306.°00	+10.°00	57.1 ± 1.0	−11.5	460.6 ± 5.3	−17.3 to −5.8
IAR10	330.°50	+10.°00	50.6 ± 0.8	+3.1	387.9 ± 6.0	−2.6 to +8.9

the polynomial varied between 4 and 7. The objetive in each case was to correct the baseline in the best possible way without affecting features which corresponded obviously to the HI signals and without introducing ripples. This was possible because each spectrum was treated individually;

4. After removing the baseline, the entire profile was multiplied by a constant value, in order to convert the observed antenna temperature scale into a brightness temperature one. The factors were derived from the calibration points observed immediately before and after each cell.

The cold points were individually reduced following a similar procedure. The data reduction itself was carried out using the DRAWSPEC program (Liszt 1987), and a local version of it, especially developed by E. Bajaja (1999) to meet the requirements of our observing scheme. Using this especially tailored program, the data reduction process was considerably speeded up.

Once a given cell was fully reduced, a minimum of three and a maximum of five positions out of the total 25, were reobserved with a shorter integration time, as a consistency check on the brightness temperature scale. When the reduced profiles of this new set of observations didn't differ from the original ones by more than 5%, the corresponding cell was included in the final survey database. The upper limit of 5% was set for low latitude cells ($|b| \leq$ 60°), while for high latitude ones this criterion was relaxed, and a higher value of 10% was adopted. This was because at high latitudes the HI emission is usually weak and the contamination by stray radiation could be quite different among both sets of observations, which were usually separated by intervals of about three to nine months from each other.

Table 3. Cold points for the IAR survey

Point	Gal. Long.	Gal. lat.
COLD1	11.°44	−59.°82
COLD2	221.°98	−52.°01
COLD3	233.°23	−27.°54
COLD4	261.°00	−40.°00
COLD5	347.°31	−75.°54

3. Main scientific drivers

The main scientific drivers of this new high sensitivity survey are the study of:

– The filamentary structures of the ISM, which under a variety of names such as shells, supershells, bubbles,

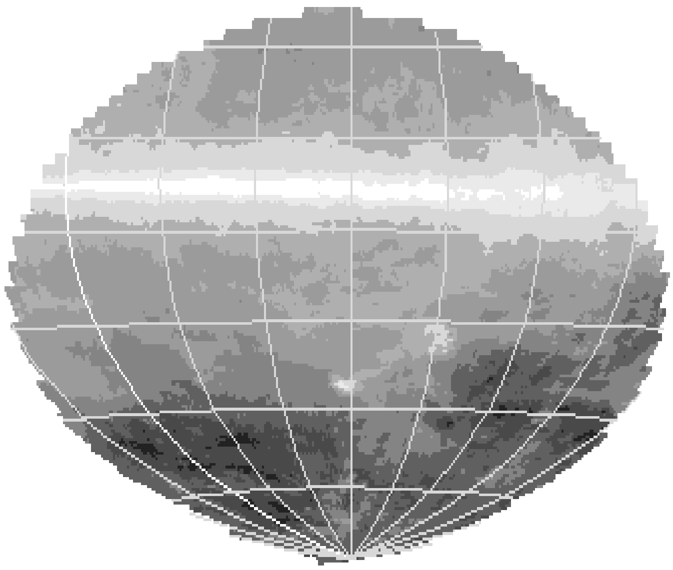

Fig. 1. Southern sky HI distribution from the IAR Survey. The velocity range is -450 to $+400$ km s^{-1}. The galactic coordinates are drawn every 20° in longitude as well as in latitude. The lighter line in longitude indicates $l = 0^\circ$. The gray scale code to the HI column density goes from zero (black) to about 2 10^{22} cm^{-2} (white)

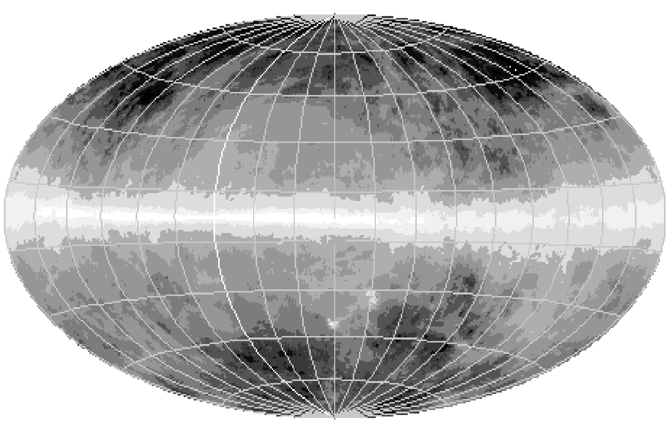

Fig. 2. Same as Fig. 1 but for the whole sky. The IAR Survey has been complemented here with the northern sky survey made by Hartmann & Burton (1997)

worms, and so forth, are known to exist. The sizes and motions of these structures reveal aspects deeply rooted to the macroscopic energetics of the ISM. In particular, two systems which are outstanding for their very large extensions in the southern sky, are the shells surrounding the Sco-Cen association and the region of the Gum nebula;

- The Magellanic System, including in this definition the Magellanic Clouds, the intercloud gas, and the Magellanic Stream;
- The distribution and morphology of the so called High Velocity Clouds;

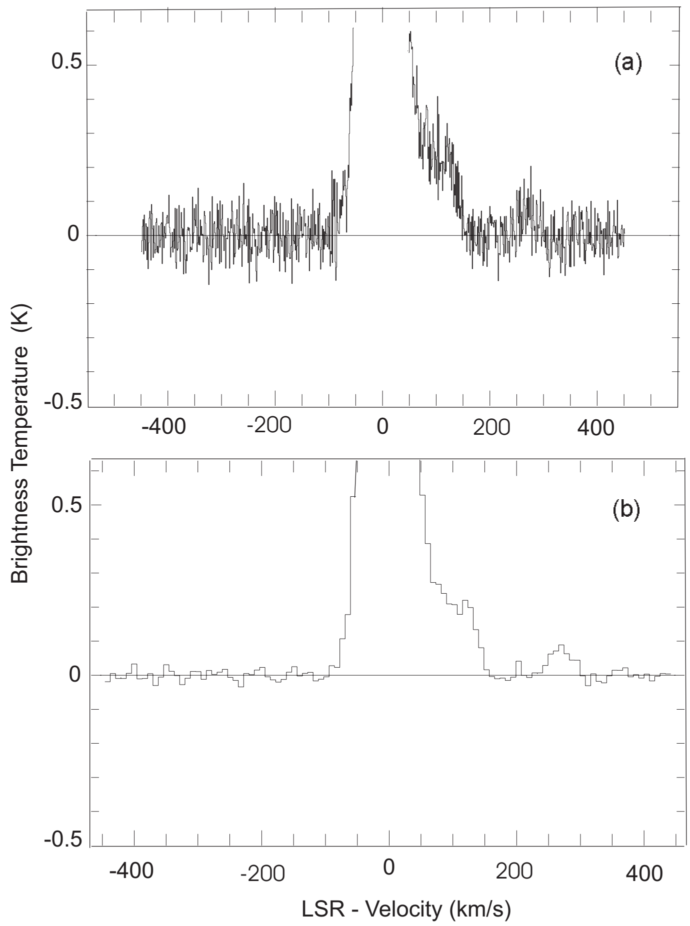

Fig. 3. HI profiles from the IAR survey at $l = 293\overset{\circ}{.}5$; $b = 10\overset{\circ}{.}0$: **a)** original data; and **b)** convolved to a velocity resolution of 8 km s^{-1}

- New details of the galactic structure in classical items like the spiral arms, the warp, the rotation curve, the central region, and the Local Arm;
- The characteristics of the neutral phases of the ISM like relative abundances, z-extension, and filling factors;
- The gaseous counterpart of the infrared interstellar cirrus;
- The regions of exceptionally low total HI column density;
- The gas–to–dust relation.

The results of the IAR HI Southern Sky Survey[1] have been used to produce Figure 1, in which the integrated neutral hydrogen profiles, over the entire observed velocity range, are shown, on an Aitoff projection. The integrated intensities are represented by a gray scale, where the lowest intensities are represented by black, and the largest one, approximately 12000 K kms^{-1}, are depicted by white. In this figure are clearly seen both the galactic plane between

[1] This HI survey is available in its present form without a correction for stray radiation. It is made available to the entire astronomical community on the base of mutual collaboration.

$l = 240°$ and $l = 20°$ (with the galactic center in between), showing the various extensions at both sides of it, and the Magellanic System[2].

Global properties of the whole sky HI distribution can be appreciated in Fig. 2, which shows the same kind of display as Fig. 1, but with the addition of the Northern sky data as obtained by Hartmann & Burton (1997). This is the first time that such a display, with uniform data, is shown.

As mentioned above, the present survey will also be useful to build a new database of High Velocity Clouds (HVC), achieving a much better sensitivity, spatial resolution, and spatial coverage than in previous HVC surveys previously conducted (Morras et al. 1999). This new HI survey will also allow to study in much more detail some of the HVC complexes known to date. Figures 3a and b are examples of the high quality of the IAR survey. Figure 3a shows the original data, while Fig. 3b shows the same data but convolved to a velocity resolution of 8 km s^{-1}.

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[2] Additional color-images with better quality graphics at different velocity ranges, that include galactic coordinates with labels and "wedges" could be found in our Web page http://www.iar.unlp.edu.ar/HI-survey.html