A LOW RESOLUTION HYDROGEN-LINE SURVEY OF THE MAGELLANIC SYSTEM

I. OBSERVATIONS AND DIGITAL REDUCTION PROCEDURES

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Summary

A survey of neutral hydrogen in the Clouds of Magellan has been made using a digital recording system in conjunction with a multichannel receiver and a 21 ft aerial. The system has been developed for use with the 210 ft radio telescope of the Australian National Radio Astronomy Observatory at Parkes, N.S.W.

Digital recording and reduction of the data proved highly successful for the rapid handling of a large amount of data.

The results obtained confirm the high gas content of the Magellanic System and also show a considerable amount of gas between the Clouds, appearing to form a bridge.

I. Introduction

McGee and Murray (1963) have briefly described a 48-channel hydrogen-line receiver in which one complete line profile is recorded every 2 minutes. Such a rate of information gathering coupled with the great amount of detail available with the 14 min of arc resolution of the 210 ft radio telescope represent a very considerable problem in data handling. Digital methods of recording and processing have been developed to cope with the large quantities of data involved, and a pilot experiment was undertaken to test the complete system, using a 21 ft telescope.

The project chosen for this purpose was a resurvey of the Magellanic Clouds. This provided a self-contained investigation for the digital techniques and the increased receiver sensitivity and frequency stability made it likely that some worth-while extension of the earlier work of Kerr, Hindman, and Robinson might be achieved, as well as providing a useful check on the main conclusions of the earlier survey, particularly that relating to the ratio M_H/M (the mass of neutral hydrogen to the total mass) which is very high compared with our own Galaxy.

The following results were obtained:

1. The digital recording and data handling proved most effective in reducing the 250 hours of observations to printed profile form, fully corrected for various calibrations, in approximately 8 hours of computer time.

2. The earlier observation of extensive gaseous envelopes associated with the Clouds was confirmed and the total mass of neutral hydrogen in the Large and Small Clouds is in good agreement with the previous measurements.

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3. The increased sensitivity of the receiver, coupled with digital integration, made possible the detection of a tenuous link of gas which appears to stretch continuously between the two main masses.

Contours of integrated brightness and median velocity distribution are presented and the methods of calibration and reduction of the digital records is described.

II. Instrumental Techniques

(a) *Receiver*

The receiver has 48 channels of bandwidth 38 kc/s spaced at 33 kc/s intervals, over a total band of approximately 1·6 Mc/s (only 46 of these channels were used in the present investigation). The time constant of the receiver is 2 minutes and output of each channel is sampled once every 2 minutes.

The receiver was used in conjunction with a 21 ft altaz-mounted paraboloid aerial giving a resolution of $2^\circ_{.}2$ between half-power points. All observations were made at meridian transit.

(b) *Zero Level*

The zero level for the profiles was derived from records on each declination taken before and after the Cloud observation. This was found necessary because a change in aerial position caused a change in aerial spillover contribution, which in turn resulted in a slight change in receiver base level. Early attempts to calibrate this shift showed that the slope of the base line also changed slightly. It was therefore decided to derive the base level for each declination run separately.

(c) *Digital Records*

The digital record of an H-line profile is illustrated in Figure 1. This is a block of 53 pairs of characters. A character in digital recording is a single row of punched or blank positions across the paper tape. A block is a group of a certain number of characters for which the sequence is arranged by the digital program unit. A block incorporates the observational data, additional information such as, in this case, the sidereal time, marker characters, and check characters.

In Figure 1 the first pair of characters, blanks or zeros, marks the start of an H-line profile block. The next 24 pairs record the observed intensities in the receiver channel numbers 0 to 23. At this point it was convenient to introduce 2 pairs of check characters, one pair with all holes punched, the other with no holes punched. This operation and non-operation of all the punch elements on command from the program unit checks that the punching and resetting are functioning correctly. The intensities of channel numbers 24 to 47 follow as 24 pairs. The second-last pair of characters records the sidereal time and the last pair is zeros to mark the end of the block.

(d) *Calibration*

(i) *Relative Intensity*.—Day-to-day relative intensity calibrations were obtained by recording the zero signal level and a standard noise signal of approximately 60°K, before and after each observational run. These were referred to as "low" and "high" level calibrations.

The noise signal was radiated from a dipole at the vertex of the paraboloid and was produced by switching on and off the high tension voltage supply to a noise diode mounted across the dipole feed point. The switching was done in synchronism with the frequency switching of the receiver so that a noise signal appeared only in the signal band of the receiver. The signal appears equally in all channels across the receiver bandpass and serves as a means of calibrating the relative gain of each channel.

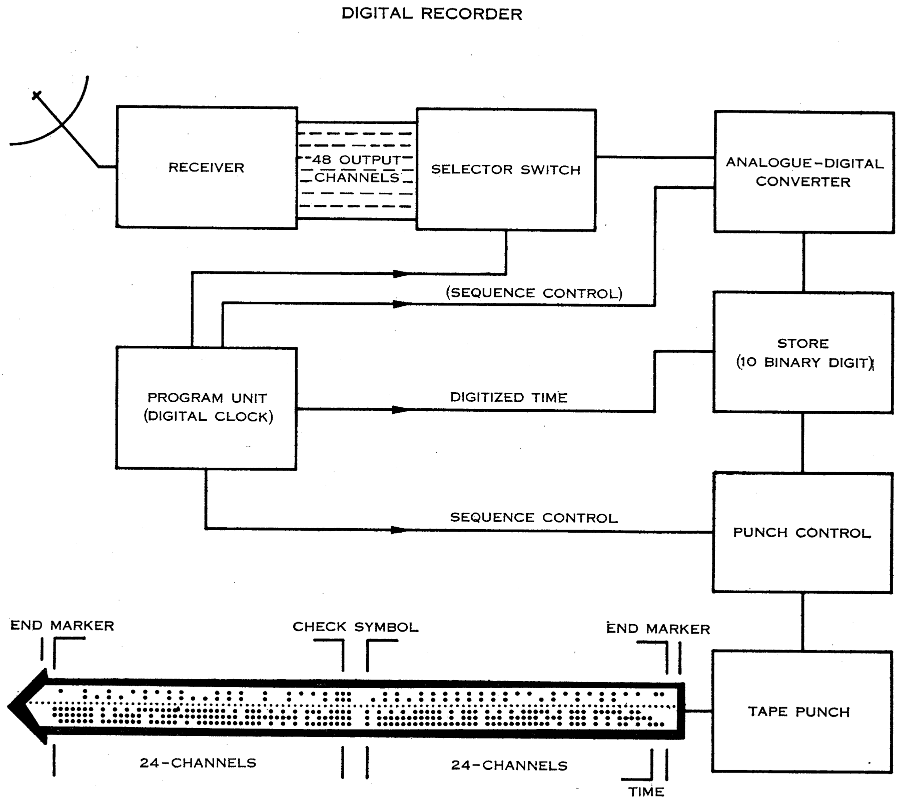

Fig. 1.—Block diagram of digital recording system for use with multichannel hydrogen-line receiver.

This method of calibration is the same as that used in previous observations with this receiver (McGee and Murray 1961) but, whereas hand reduction of the analogue records previously made it necessary to estimate an average figure for gain corrections, the digital record makes it possible to apply individual gain and zero level corrections to every channel.

The general overall stability of the receiver sensitivity may be judged from the results given in the last column of Table 1. They are calibration factors representing the daily average for the 46 channels taken during the present survey.

(ii) *Absolute Intensity.*—No absolute calibration of the multichannel receiver has yet been attempted and all previous results have been published in terms of a temperature scale obtained by comparison of common galactic profiles with the Leiden results of Muller and Westerhout (1957).

Similar comparison with the Potts Hill results of Kerr, Hindman, and Gum (1959) lead to a temperature scale which differs very little from that previously used. The present results are in terms of this aerial temperature scale, which must be multiplied by an aerial gain factor to obtain brightness temperature.

(iii) *Frequency.*—In estimating the stability and accuracy of the receiver frequency the contribution of three separate sections of the receiver must be taken into account: the first local oscillator, the second local oscillator, the tuned filters.

All frequency measurements were made using a counter-type frequency meter. Its accuracy was found to be within 5 parts in 10^8 by the frequency standards section of the National Standards Laboratory, Division of Applied Physics.

The first local oscillator frequency is derived by multiplying a frequency of 38·5 Mc/s by 36. The 38·5 Mc/s is produced in an overtone crystal oscillator. The frequency of the crystal oscillator remained within $\pm 0 \cdot 07$ kc/s for the whole of the observing period.

The second local oscillator frequency is taken directly from the same crystal oscillator.

The filter frequencies were set to an accuracy of $\pm 0 \cdot 5$ kc/s, and checks made over a number of years have shown them to remain within these limits for several months at a time.

The overall frequency stability then can be stated in terms of radial velocity error as $\pm 0 \cdot 6$ km/s.

With the frequencies of the local oscillator and the filters known, a radial velocity can be allotted to each channel. In the digital records a radial velocity value was represented by a channel number to one decimal place. A further error of $\pm 0 \cdot 4$ km/s is introduced in this way.

The 24th channel frequency was adjusted so that the centre of this channel represents a radial velocity of 221 km/s with a range of velocity over 46 channels of about 320 km/s.

The overall estimated error in radial velocities in this survey from sources of error other than noise fluctuations then is ± 1 km/s.

III. The Digital Recorder

The digital system was made to be self-contained, consisting of a program unit, for control of the various recording functions, an analogue-to-digital converter, and a paper tape punch with associated control circuits. Figure 1 is a block diagram of the recording system.

The program unit consists of a clock driven at the sidereal rate, with shafts giving the following rates:

52 revolutions in 2 minutes,
1 revolution in 2 minutes,
1 revolution in 1 hour,
1 revolution in 24 hours.

The first pair of these shafts is fitted with a series of optical cams, which operate relays to provide the switching for selection of the quantities to be punched on the output tape.

The 1-hour and 24-hour shafts are fitted with binary coded disks to produce a digital version of the sidereal time, which is read from the disks at 2-minute intervals.

The analogue-digital (A-D) converter is of the shaft rotation type with a photoelectric readout controlled by a flash lamp. Figure 2 is a schematic representation of this encoder.

Figure 3 shows the layout of the code disk, which was prepared to give 1024 numbers in 324 degrees of rotation. This corresponds to the full-scale movement of the potentiometer shaft of the Leeds and Northrup potentiometric recorder used with the receiver.

A cyclic progressive binary code (the Gray code), in which a change from one number to the next involves a change of only one binary digit, was used on the

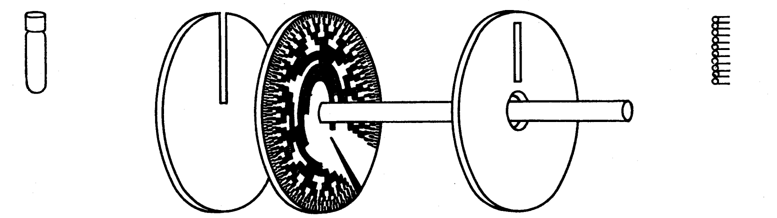

Fig. 2.—Schematic diagram of the arrangement of the digital shaft encoder.

converter disk to avoid errors which arise when readings are taken off the disk in positions overlapping two numbers. Thus the error in a given reading can never be greater than one-thousandth of the full-scale deflection of the recorder.

A reading from the converter is obtained by flashing the lamp L of Figure 2. The number corresponding to the shaft position is then sensed by the ten photo-transistors P_0 to P_9 through the reading slot S.

When a number is read from the code disk it is first stored in a binary store consisting of 10 bistable multivibrators. On receipt of an initiating pulse from the program unit the number is punched on to five-hole paper tape. As mentioned in Section II(*c*), two characters are used to represent a number, the most significant digits being in the first character.

IV. Data Reduction

We have seen that the digital record consists of a number of blocks of H-line profiles in which the channel intensities and sidereal times are included and that the channel numbers themselves give radial velocity information. In addition, the declination setting of the aerial, constant for one day's run, the date of observation, and the equivalent radial velocity at which the receiver had been set are required before reduction can take place.

(*a*) *Editing*

The first step in data reduction was to edit the punched tape; two checks were carried out during the editing process:

(i) The tape was visually inspected for block markers and central check characters, and

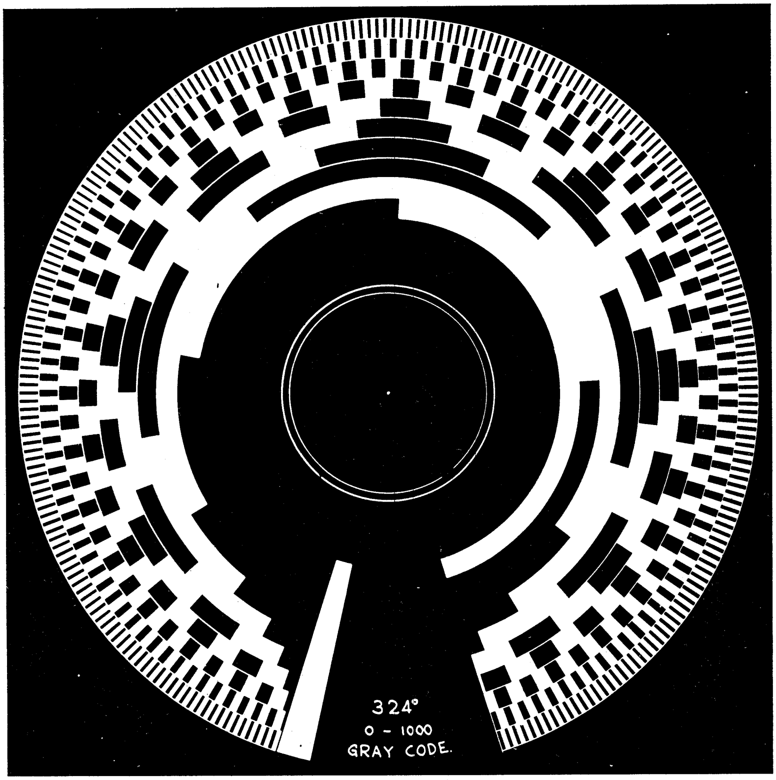

Fig. 3.—The C.P.C. (Gray code) disk pattern used in the digital encoder. The 324° of shaft rotation is divided into 1024 steps.

(ii) the tape was passed through a reader counting the number of characters in each block. These checks were considered worth while to eliminate any hold-up of data reading at the computer. Four of the original tapes were rejected at this stage.

(*b*) *The Calibration Tape*

For each data tape a calibration tape was prepared by selecting suitable sections of the "high" and "low" level calibration and a base-level run usually the same as the "low" level. The calibration tape, fed into the computer at the beginning of each observational run, produced base-level corrections and channel gain factors which were stored in the program ready for use in reducing the observational data.

Ten or twelve blocks were averaged in each calibration run, thus producing a set of calibration factors substantially smoothed from receiver noise fluctuations.

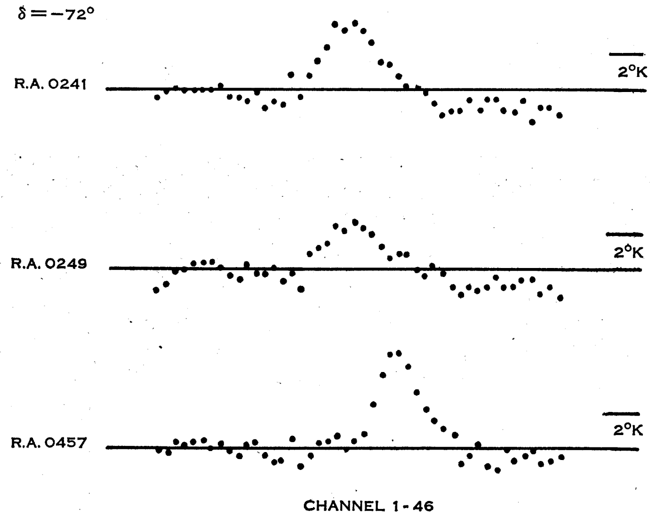

Fig. 4.—Low level H-line profiles showing residual base-line slope after partial reduction.

(c) *Change of Base-line Slope*

In a perfectly stable receiver the complete intensity information would be obtained by subtracting the receiver base level from the observed deflection and then multiplying by a gain factor. It was found, however, that the base line of

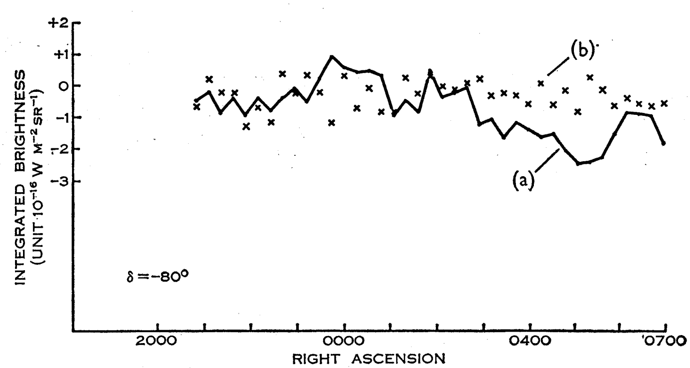

Fig. 5.—Plot of integrated brightness showing in curve (*a*) the effect of receiver base-line drift and in curve (*b*) the effect of the correction adopted in the reductions.

profiles corrected in this way showed a small amount of slope which varied during observations (Fig. 4). The effect was traced to diurnal temperature changes in the input circuit of the receiver.

The result of this effect is also seen in Figure 5, curve (*a*), where the plot of integrated brightness, which is expected to be zero for the chosen region of the sky at Dec. $-80°$, shows a drift to negative values during part of a night's run. The drift is of just the right amount to be accounted for by the change of slope in the base level.

A second-order correction was applied to correct the base-line slope. The level of the first and last four channels was used to determine the slope. Figure 5, curve (*b*) shows the result of applying such a correction to the Dec. $-80°$ integrated brightness. The deviation is then within $\pm 10^{-16}$ W m^{-2} sr^{-1}, equivalent to an error of $\pm 0 \cdot 2$°K/channel across the profile.

To be valid the correction for base-line slope must be made from channels which are not affected by line radiation. Such channels could always be found in the present Magellanic System survey. Figure 6 shows a plot of channels 1, 4, and

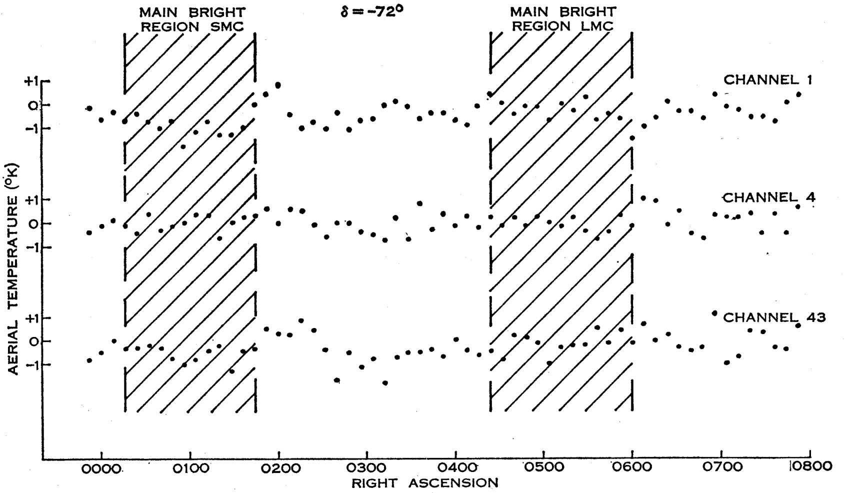

Fig. 6.—Plot of end-channel variations during a run across the central region of the Magellanic System.

43 of a run at Dec. $-72°$. At this declination the signal from both Clouds is intense and at its widest spread in frequency. No signal can be seen on these records. Other declinations were checked in the same way.

Figure 7 shows some samples of fully corrected profiles selected near the maximum of each Cloud and in the region between.

(*d*) *Channel Deviation*

A calculation of the r.m.s. noise fluctuations on the records indicated that the inherent receiver noise fluctuations were less than $\pm 1 \cdot 8$°K. Figure 6 gives some idea of the overall fluctuations when the observed channel intensities were integrated digitally over four observed profiles.

As a check for faults in recording, a routine was included in the reduction program which checked whether the fluctuation of any channel reading in a group was greater than three times the r.m.s. fluctuation. Any such channel was identified by a tag in the print-out thus making it possible to scan both digital and analogue records for faults.

About 1% of the channels in profile blocks where signals could be expected were marked in this way. But the only faults found of a serious nature were three occasions when blank characters had been punched in error. The rest of the channels marked were in high intensity regions of both Clouds where rapid changes in the spatial distribution of the radiation probably account for the apparently larger scatter of the observed points.

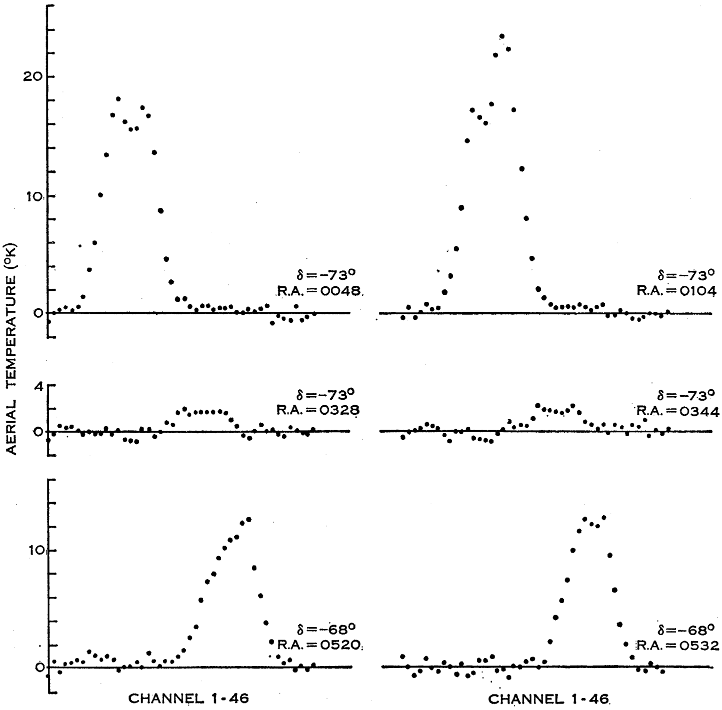

Fig. 7.—Set of profiles fully corrected for calibration factors and base-line drift. The samples are chosen near the centres of the Large and Small Cloud and in the bridge region between the Clouds.

(e) *Extra Parameters Calculated*

Besides the corrections of profiles by means of the computer, several profile parameters were calculated and printed out while the data were being processed. This possibility is one of the great advantages of digital data processing and the amount of calculating will vary, depending on the data and the aim of the experiment. In the present case five quantities were derived as follows:

(i) The integrated brightness $B_{\text{int.}} = (2k/\lambda^2)\int T(V)\mathrm{d}V$ was calculated. It is proportional to the area under the profile and so is found very simply by summing the channel intensities and applying an appropriate scaling factor. $B_{\text{int.}}$ was printed at the end of each profile.

(ii) The median radial velocity for each profile was calculated as a channel number to the first decimal place. The median velocity is defined such that the integrals of brightness on either side of the median velocity are equal.

(iii, iv) Two quartile velocities were similarly determined which may be used to describe the distribution of velocity along a given line of sight.

(v) The final calculated parameter printed out was the average right ascension for the profile corrected for the receiver time constant effects.

(*f*) *Output Tape*

The final result from the reduction undertaken is an output tape from the computer which is immediately usable to obtain a printout. The printout consists of a series of blocks of information, each block containing:

(i) 46 channel intensities expressed in aerial temperature—the H-line profile

(ii) The right ascension of the observation

(iii) The integrated brightness of the profile

(iv) The measured first and third quartile and median velocities as channel numbers.

(The other sky coordinate, declination, is constant for each output tape.)

(*g*) *Velocity Correction*

No attempt has been made in this preliminary program to include the velocity corrections in the data reduction program. They were computed separately in two stages. The observed velocities were first corrected for the Earth's orbital motion to give the conventional radial velocity. A second correction was then applied to take account of solar motion and galactic rotation. The exact nature of the corrections applied in this step will be discussed in detail in a subsequent paper.

(*h*) *Computer Program*

The "SILLIAC" of the Adolph Basser Computing Laboratory, School of Physics, University of Sydney, was used for the reductions just described. Figure 8 is a schematic diagram showing the layout of the computer functions.

The actual program was written in the form of routines for each of the calculations involved, the whole being under the control of a master routine which converts the cyclic numbers read into the computer to natural binary, allocates storage, and generally controls the course of the operations.

A total of approximately 250 hr of observations was processed through the computer in about 8 hr. Velocity correction calculations required 15 min of computer time.

The next step in such a program as this is the automatic plotting of results, but owing to unavailability of equipment this step was not taken in the present investigation.

The experience gained with this project shows that very worth-while gains in reduction time attend the use of digital recording and reduction. A considerable increase in accuracy is also inherent in this particular problem because of the possibility of applying individual channel corrections rather than overall smoothed values.

Keeping the programming in easily adjusted units also has its advantages, as indicated by the correction of residual base-line slope, which was added after trial reductions had been made. In any case, when reducing fundamentally new data the course of the reductions cannot be determined in full beforehand.

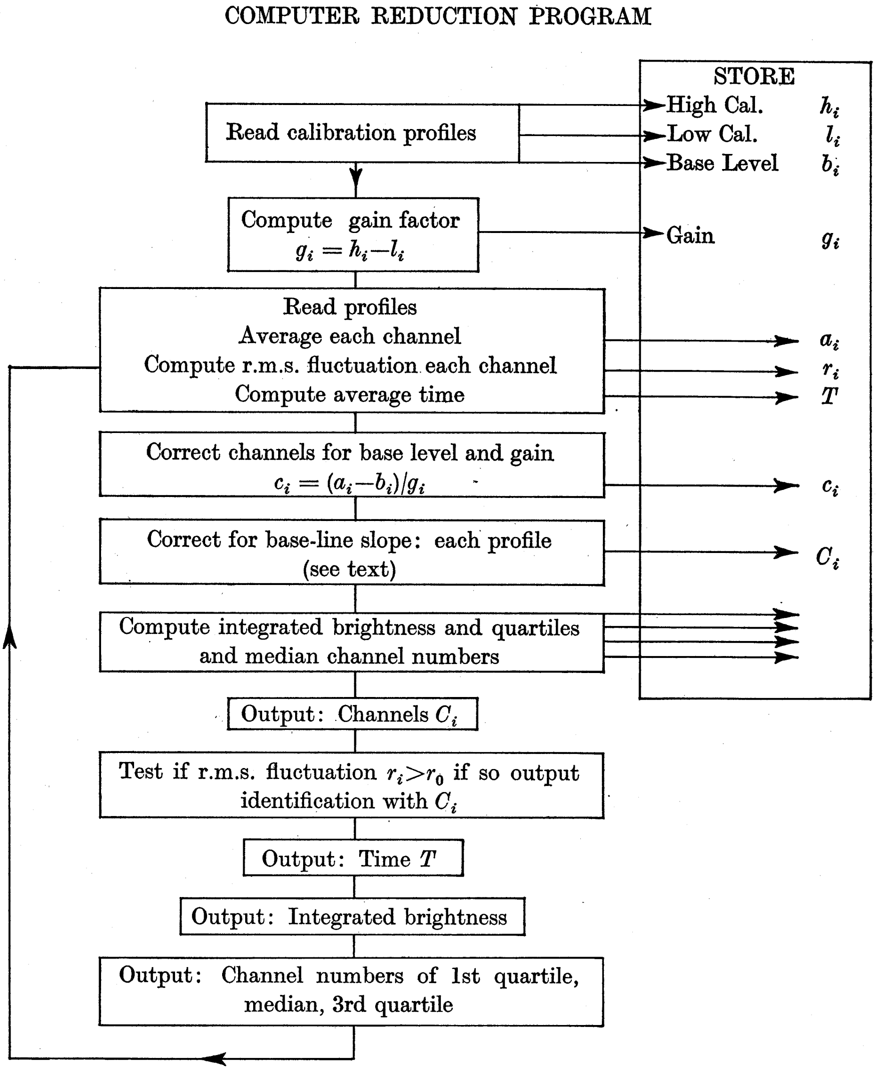

Fig. 8.—Simplified flow diagram of the basic functions of the reduction program.

V. Results

(a) Observations

The observations were all obtained with the aerial beam stationary in the meridian plane. One set of observations consisted of a series of H-line profiles at intervals of 2 min, recorded at a constant declination over the approximate range of right ascension 22^h–08^h. Declination tracks were chosen at 1° intervals.

Recording a profile once every 2 min using a 2°.2 aerial beam in the declination range from —60° to —80° gives from 8 to 25 profiles per beam width. Digital integration was used in the final reduction of the data to provide a smoothed profile every 1° in the sky along the constant declination tracks.

A total of 28 runs were taken between August 28 and October 4, 1960, of which 24 where finally chosen as usable. The other four were discarded because of faults in the digital system. Table 1 gives a list of the recording dates, times, and declinations.

Table 1

DETAILS OF DIGITAL RECORDS OF M.C. RADIATION*

Dec.	Date 1960	R.A. of Obs. Start	R.A. of Obs. Finish	Cal. Factor	Dec.	Date 1960	R.A. of Obs. Start	R.A. of Obs. Finish	Cal. Factor
−60	Sept. 29/30	2250	0830	41	−71	Aug. 28/29	2332	0842	52
−61	Sept. 9/10	2130	0820	50	−71	Sept. 23/24	2320	0834	50
−62	Sept. 28/29	2150	0840	53	−72	Sept. 10/11	2356	0800	50
−63	Sept. 4/5	2100	0750	51	−73	Aug. 30/31	2230	0716	52
−64	Sept. 27/28	1940	0820	46	−73	Aug. 31/ Sept. 1	2200	0720	52
−64	Oct. 1/2	1940	0810	54	−73	Sept. 25/26	2234	0750	54
−65	Sept. 6/7	2250	0820	50	−74	Sept. 30/ Oct. 1	2330	0840	54
−66	Sept. 13/14	2050	0738	51	−75	Sept. 1/2	2134	0740	52
−67	Sept. 3/4	2230	0830	52	−76	Sept. 24/25	2240	0810	46
−68	Sept. 12/13	2230	0810	50	−77	Sept. 5/6	2320	0710	52
−69	Sept. 2/3	2250	0950	52	−78	Sept. 26/27	2356	0810	55
−70	Sept. 20/21	0000	0820	44	−79	No record			
					−80	Sept. 11/12	2050	0820	50

* Copies of the above digital records are available with calibration tapes, from the Radiophysics Laboratory, CSIRO. The printed reduced data are also available.

Pen recordings were taken at all times in parallel with the digital recordings, for receiver monitoring purposes. Pen records were also used to check channels queried by the digital reduction program. Figure 9 shows a section of the analogue record near the centre of the Small Cloud.

(b) *Integrated Brightness Contours*

Constant declination sections through the Clouds, showing the variation of integrated brightness with right ascension, were plotted directly from the reductions. Three such sections from completely independent runs at Dec. —73° are shown in Figure 10. The overall scatter in these curves represents a deviation of $\pm\frac{1}{4}$°K over 46 channels.

The most striking feature of the contour map of integrated brightness in Figure 11 is that the gas appears to envelope the two galaxies completely. The previous contours produced by Kerr, Hindman, and Robinson (1954) are very similar, particularly when allowance is made for a difference of aerial resolution (2°.2 compared with 1°.5). There was also a considerable improvement in receiver sensitivity, and

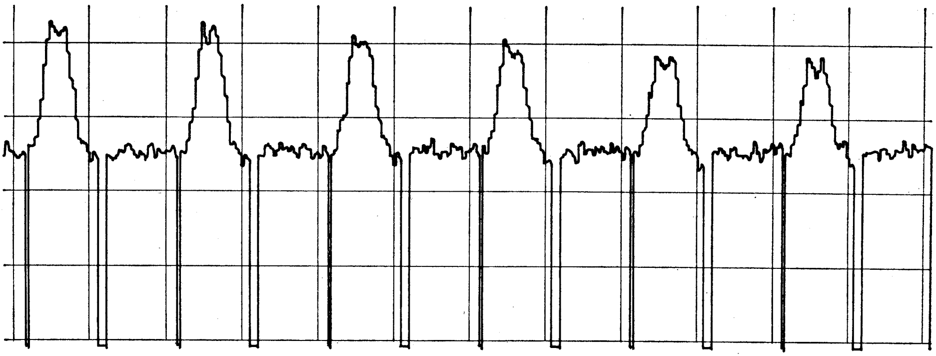

Fig. 9.—Copy of section of the chart record showing several profiles near the centre of the SMC, Dec. $-73^\circ.0$, R.A. $23^h 50^m$ to $23^h 40^m$.

this, coupled with the effect of digital integration, has raised the sensitivity in the low density region between the Clouds to the point where the gas now appears to form a continuous bridge.

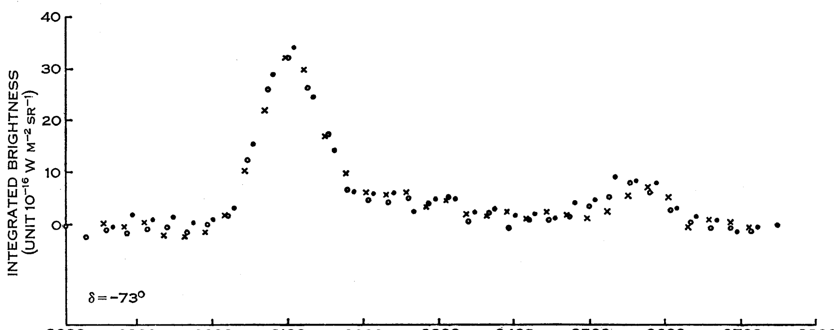

Fig. 10.—Comparison of two independent sets of measurements of the variation of integrated brightness along a constant declination track.

(c) *Velocity Contours*

Figure 12 is a plot of contours of median velocity corrected for the Earth's orbital motion. Here the agreement with the former work is very reasonable considering the very great improvement which has been made both in measuring and stabilizing the frequency.

Velocities further corrected for solar motion and galactic rotation will be presented and deductions concerning the rotation and motion of the Clouds will be discussed in another paper.

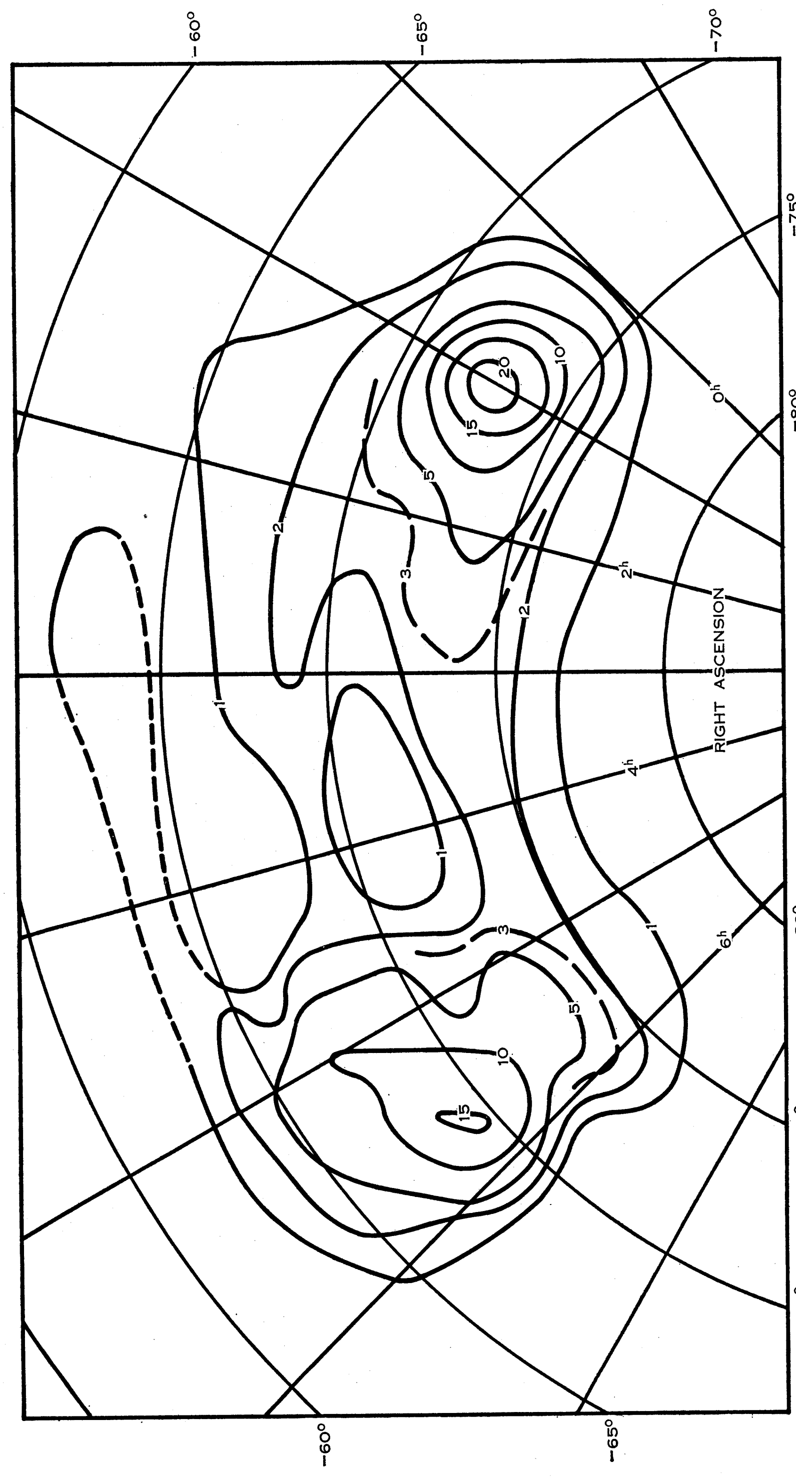

Fig. 11.—Contours of integrated brightness of neutral hydrogen in the Magellanic System. Contour unit 2×10^{-16} W m^{-2} sr^{-1}.

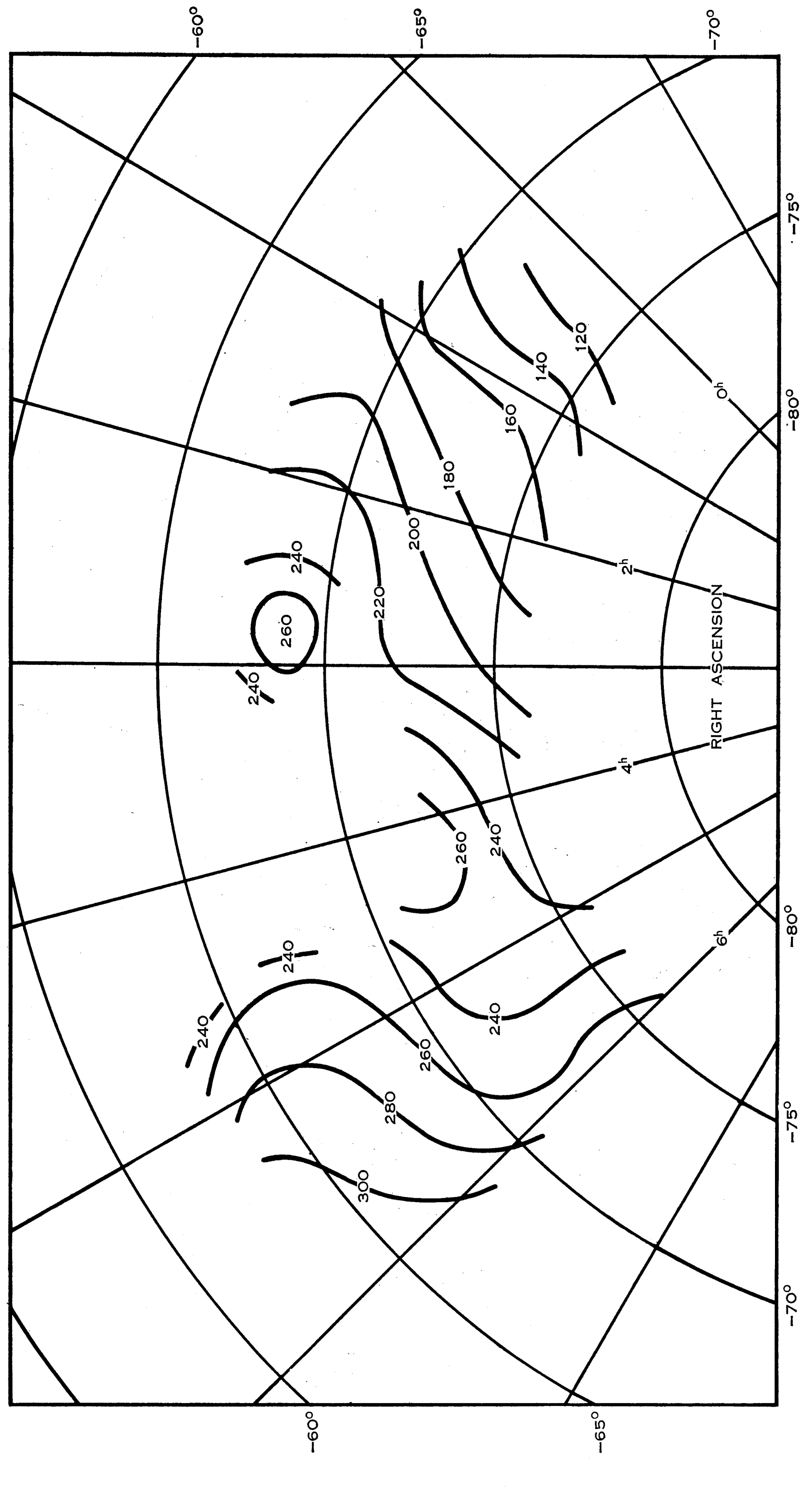

Fig. 12.—Contours of median radial velocity of neutral hydrogen profiles in the Magellanic System corrected for the Earth's orbital velocity. Contour interval 20 km/s.

(*d*) *Profiles*

Figures 13 and 14 are collections of profiles at 1° intervals over the Magellanic Cloud system. Each profile is plotted on the appropriate declination line, while the 0100 and 0530 right ascension lines have been chosen as the axes from which 1° intervals east and west are measured. The profile at each of these points is plotted

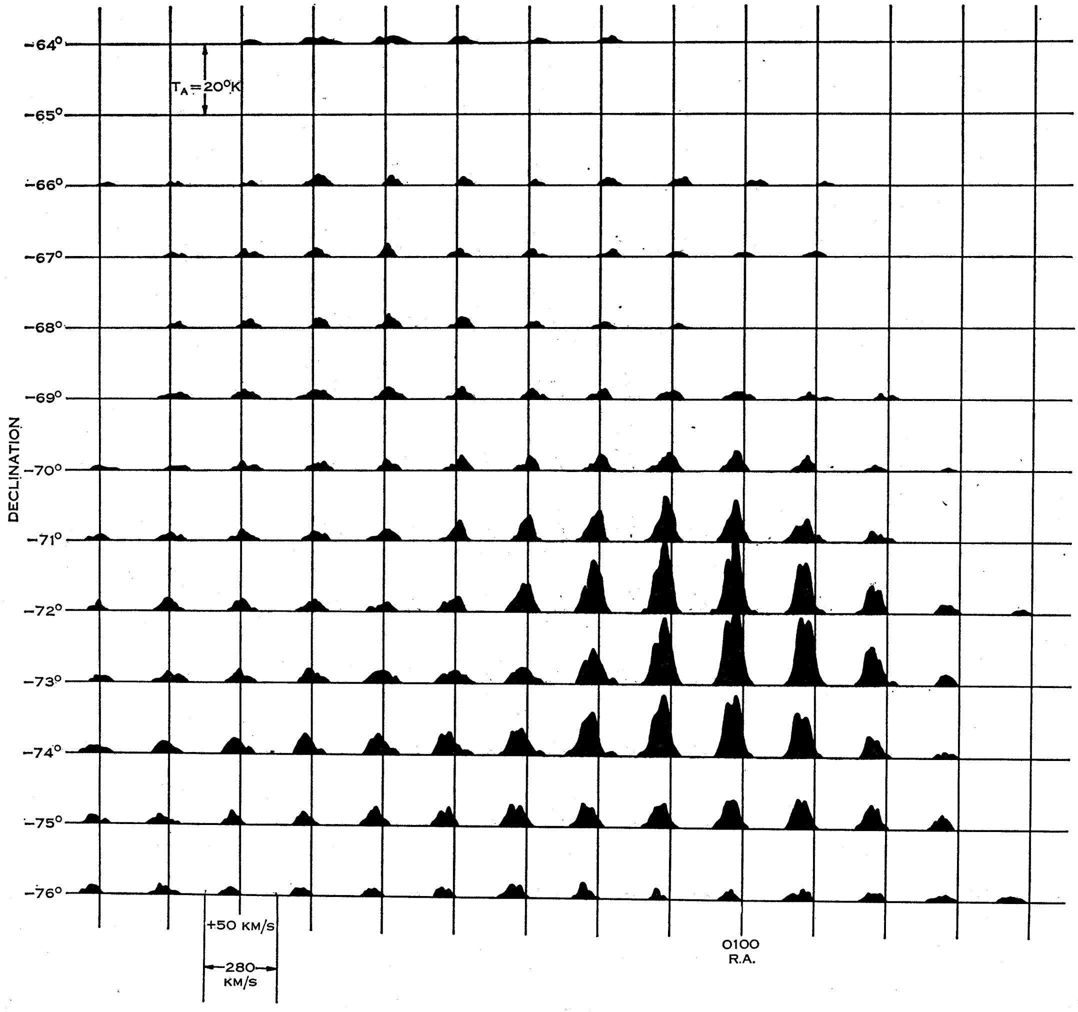

Fig. 13.—Profiles for the region of the SMC. One profile is plotted for each square degree of sky. The vertical line on each profile is at +50 km/s. Vertical line spacing is equal to 280 km/s.

so that the vertical line of each degree interval is the +50 km/s velocity point on the profile. The velocity scale is such that the distance between adjacent 1° lines represents 280 km/s. (The velocities are corrected for solar motion and galactic rotation.)

A striking feature of Figure 13 is the regular splitting into two peaks of the H-line profiles of the Small Magellanic Cloud. A discussion of the phenomenon is given in paper II (Hindman, Kerr, and McGee 1963).

VI. Conclusions

A successful trial of a digital recording system has been carried out, using a multichannel hydrogen-line receiver to observe the Clouds of Magellan. The records have been reduced to corrected profile form by means of an automatic digital computer.

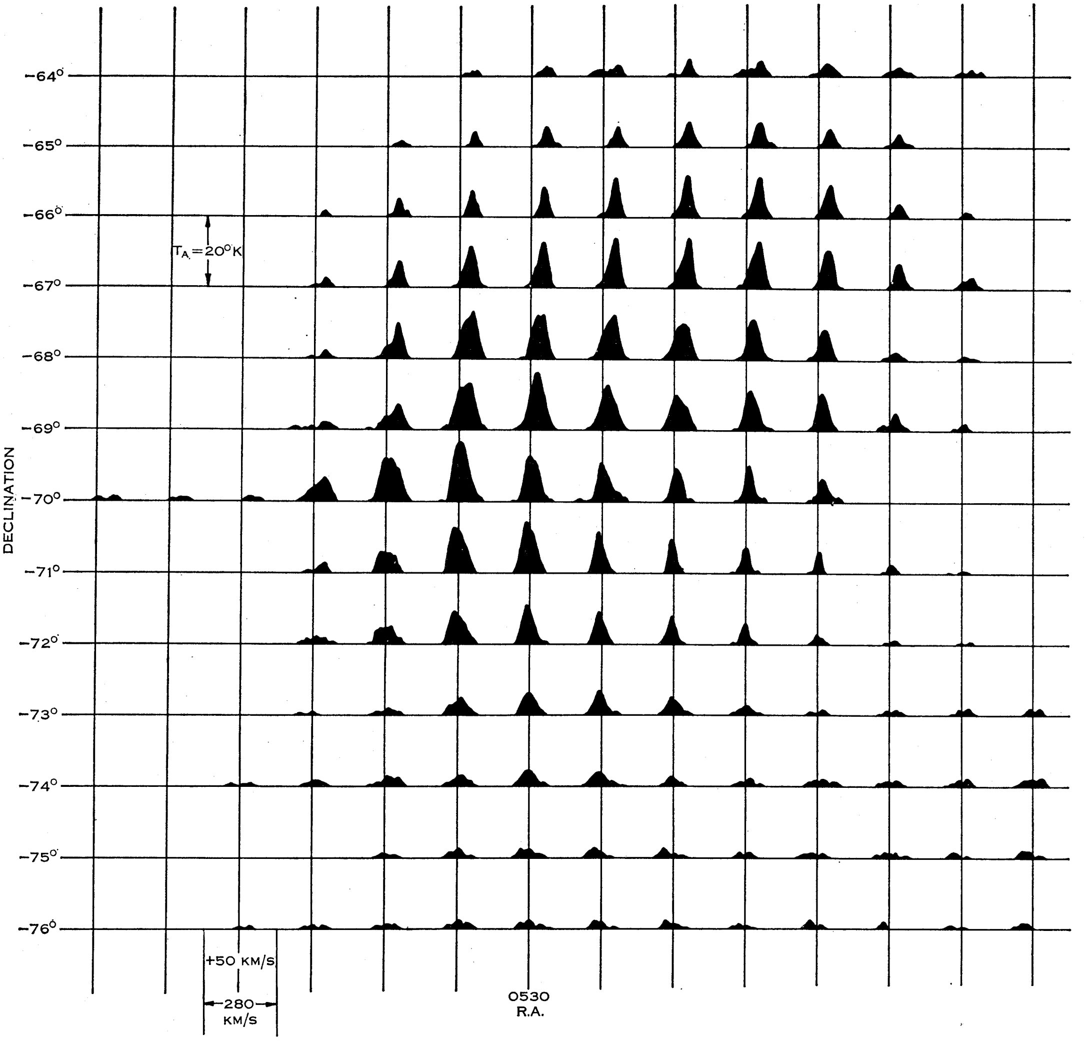

Fig. 14.—Profiles for the region of the LMC. One profile is plotted for each square degree of sky. The vertical line on each profile is at +50 km/s. Vertical line spacing is equal to 280 km/s.

The time spent on reduction of records has been greatly reduced compared with that required for analogue records. The addition of some automatic plotting would eliminate most of the tedious hand work from reduction of this type of radio-astronomy recording.

Digital recording has made possible the more rigid application of calibration data, leading to the detection of a second-order receiver effect. Examination of reduced results while assembling the reduction program can lead to more effective correction of observed data.

On the astronomical side, the previous results concerning high gas content and wide distribution of neutral hydrogen have been confirmed and in addition it seems probable from the present results that the Clouds are in fact linked by a tenuous bridge of gas.

The detection of such low level radiation is assisted considerably by the use of digital integration. Digital methods should lead to greatly increased efficiency in the preparation of extensive observational results for assimilation by the astronomer.

VII. References

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