21 CM HYDROGEN-LINE SURVEY OF THE LARGE MAGELLANIC CLOUD

I. STELLAR, NEBULAR, AND NEUTRAL HYDROGEN RADIAL VELOCITIES

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[*Manuscript received May* 28, 1964]

Summary

A recent survey of the neutral hydrogen in the Large Magellanic Cloud with a 14′·5 beam and the 48-channel H-line receiver has afforded an opportunity to compare the radial velocities of a number of optical objects with the radial velocities of the hydrogen gas in their directions.

The motions of 54 of the 72 supergiant stars and all 42 of the Hα nebulae, whose radial velocities were measured by Feast, Thackeray, and Wesselink (1960); Feast (1964), are shown to be closely related to the gas motions.

Some other topics such as "run-away" stars and reddening of stars are briefly discussed.

I. Introduction

A recently completed survey of the neutral hydrogen in the Large Cloud of Magellan (LMC) with an aerial resolution of 14′·5 between half-power points has afforded the opportunity of comparing individual radio and optical radial velocities. The values of the optical radial velocities for both the stars and gaseous nebulae are principally due to the contributions of Feast, Thackeray, and Wesselink (1960) and Feast (1964).

The comparison has additional interest because for some time controversy has existed concerning the apparent correlations, both positive and negative, between the spatial coincidence of O and B stars and the concentrations of neutral hydrogen in our own Galaxy. Muhleman and Walker (1964) conclude that, if the currently used Leiden-Sydney model of HI distribution be invoked, a significant negative correlation exists between O stars at positions in space determined by optical methods and dense HI regions. On the other hand, Fletcher (1963), using the Schmidt velocity–distance model to position both stars and gas, finds a strong positive correlation.

The LMC is believed to be a rather flattened system and, in general, the observations of the gas distribution are not confused by numbers of spiral arms or concentrations in the same line-of-sight. The introduction of velocity–distance models is therefore unnecessary.

Comparisons were possible with some 70 stellar velocities measured by Feast, Thackeray, and Wesselink (1960), though many more values are required to make a comprehensive investigation of the detailed relationship between stellar and gas motions.

The recent publication of 42 nebular radial velocities by Feast (1964) has enabled an extended comparison of velocities in neutral and ionized gases to be made for the first time.

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Table 1

SUPERGIANT STARS AND NEUTRAL HYDROGEN

Group A

Star	Radcliffe No.	HI Position (1963)		Radial Velocities (km/s)			HI-line Half-width (km/s)	Spectral Class	HI Peak T_A (°K)
		R.A. h m	Dec. ° ′	Star	HI Peak	Δ_{HI-*}			
268654	R52	04 49·6	−67 36	+266	+280	+14	29	B8I	22
31673	R54	04 52·4	−69 24	250	256	+6	27	Neb	39
268718	R55	04 52·4	−69 24	268	256	−12	27	B9Ieq	39
268653	R57	04 53·3	−67 00	301	290	−11	28	B31	31
268729	R58	04 53·6	−68 48	271	270	−1	30	B51	18
268757	R59	04 54·5	−69 12	258	259	+1	30	G5Ia	33
268675	R61	04 54·0	−66 48	286	291	+5	32	Ao	18
32034	R62	04 55·4	−67 12	295	294	−1	45	B9Ie	15
32228	R64	04 56·3	−66 36	275	275	0	33	WC6+o8	15
268809	R65	04 56·1	−69 24	258	256	−2	32	B1Ia	18
268835	R66	04 56·6	−69 48	271	272	+1	17	Aeq	7
32763	R67	04 59·4	−70 12	244	244	0	18	Pec	13
270933	R68	04 59·7	−65 48	313	296	−17	34	B8I	9
270949	R70	05 00·7	−65 48	300	300	0	34	B3I	12
268993	R72	05 03·1	−70 48	237	249	+12	35	AoIa	10
268907	R73	05 03·0	−67 00	305	287	−18	31	B8Ia	24
268939	R74	05 04·5	−67 12	299	286	−13	40	BIe	24
268946	R75	05 05·7	−66 48	297	300	+3	26	AoIa	31
33579	R76	05 05·8	−68 00	253	270	+17	56	A3Ia	15
269050	R78	05 07·7	−68 36	238	242 284	+4	44 (est)	BoIa	13
269172	R80	05 10·5	−71 24	231	240	+9	22	AoIa	17
269217	R82	05 13·9	−69 24	236	250	+14	22	Pec	25
269227	R84	05 14·1	−69 36	262	251	−9	28	Pec	25

271182	R92	05 20·9	−65 48	322	304	−18	27	F8Ia	10
271191	R94	05 21·9	−65 48	291	308	+17	27	BComp	10
Anon	R95	05 21·9	−65 48	329	308	−21	27	BoI	10
271213	R96	05 22·3	−72 00	241	237	−4	30	B3I	17
Anon	R97	05 21·9	−65 48	308	308	0	27	B0·5Ia	10
271192	R98	05 21·9	−65 48	308	308	0	27	AoIa	10
269475	R100	05 23·3	−71 48	251	239	−12	26	B3I	23
269547	R101	05 27·1	−71 36	251	237	−14	26	B3Ia	35
271279	R104	05 28·0	−65 48	306	308	+2	28	AoIa	15
269599	R65	05 28·0	−69 12	268	255	−13	70	B8I	13
Anon	R108	05 30·2	−67 24	318	311	−7	23	Pec	15
269661	R111	05 31·2	−69 36	260	260	0	58	B9Ia	12
269660	R112	05 30·8	−71 00	237	238	+1	28	B2Ia	31
269676	R113	05 31·8	−71 00	244	242	−2	29	O6e	25
269787	R119	05 34·9	−67 00	312	296	−16	37	AoIa	4
269797	R120	05 35·2	−67 24	288	305	+17	29	B8Ia	17
269801	R121	05 35·3	−67 24	319	305	−14	29	B9Ia	17
37836	R123	05 35·8	−69 42	267	270	+3	39	Pec	34
269845	R125	05 36·3	−67 24	292	304	+12	32	B3I	16
37974	R126	05 37·1	−69 24	258	277	+19	47	Pec	25
269858	R127	05 36·8	−69 30	284	275	−9	41	Pec	30
269859	R128	05 36·8	−69 30	268	275	+7	41	B1I	30
269896	R129	05 37·8	−68 54	273	275	+2	33	BoIa	60
269962	R131	05 38·0	−69 06	269	278	+9	41	B9I	51
38268	R136	05 38·0	−69 06	274	278	+4	41	O+WN	51
Anon	R143	05 39·4	−69 12	263	271	+8	50	F7Ia	49
269953	R150	05 40·5	−69 42	241	254	+13	38	GoIa	70
269992	R152	05 41·9	−69 48	258	257	−1	39	B2·5	49
270086	R153	05 45·8	−69 00	253	262	+9	38 (est)	A1Ia	30
270151	R154	05 49·0	−70 06	242	236	−6	30	B1I	36
270196	R155	05 51·8	−70 12	248	241	−7	32 (est)	B1·5Ia	10

TABLE 1 (*Continued*)

Group B

Star	Radcliffe No.	HI Position (1963)		Radial Velocities (km/s)			HI-line Half-width (km/s)	Spectral Class	HI Peak T_A (°K)
		R.A. h m	Dec. ° ′	Star	HI Peak	Δ_{HI-*}			
270754	R51	04 47·5	−67 12	+306	+270	−36	27	B1·5Ia	30
268605	R53	04 50·4	−67 48	309	267	−42	29	BoIa	15
268623	R56	04 52·5	−66 48	312	287	−35	28	B2Ia	27
269006	R71	05 03·0	−71 24	198	246	+48	23	B2·5Ieq	15
269101	R79	05 10·7	−68 48	302	260	−42	49	B5I	24
269128	R81	05 10·7	−68 48	227	260	+33	49	B2·5Ieq	25
269321	R85	05 18·5	−69 24	292	256	−36	43	B5Iae	27
269333	R87	05 18·5	−69 12	286	252	−34	40	W+B1I	18
35343	R88	05 18·5	−69 12	295	252	−43	40	Aeq	18
35517	R89	05 19·8	−69 36	285	258	−27	48	BoI	22
269445	R99	05 22·8	−68 00	278	300	+22	28	Pec	52
269546	R103	05 27·5	−68 48	298	270	−28	31	B3Ip	12
269644	R107	05 30·1	−67 36	336	300	−36	55	B6Ia	16
269700	R116	05 31·7	−68 36	252	271	+19	27	B1·5Iaeq	42
269723	R117	05 32·4	−67 48	317	300	−17	19	GoIa	45
269781	R118	05 34·9	−67 00	342	296	−46	37	AoIae	4
269810	R122	05 35·2	−67 36	257	298	+41	26	O6+Neb	41
Anon	R133	05 38·0	−69 06	235	275	+40	41	O8	51

II. The Observations

The radial velocities of the neutral hydrogen were measured by observing the 21-cm line radiation with the 210-ft paraboloid at Parkes, N.S.W. and the 48-channel H-line receiver described by McGee and Murray (1963).

The method of the survey was to scan the aerial along lines of constant declination at such a rate (3′ of arc per sidereal minute) that two H-line profiles per beamwidth were recorded. Declination tracks were spaced at 12′ intervals over the area of the Large Cloud and at 6′ intervals in complex regions. The spacing in right ascension was approximately 1 min.

Since the radial velocity of profile peaks varies slowly in the LMC (it is constant over regions $\sim\frac{1}{2}^\circ$ square) the small differences (mean $\leqslant 3'$) between the positions of the "optical" objects and the nearest HI observations are not significant.

The pointing accuracy of the Parkes paraboloid is within 1′ and it is estimated that the peak radial velocities are quoted to an accuracy of $\pm 1\cdot 5$ km/s.

The intensity and position data were recorded on punched paper tape and later processed for base level and sensitivity calibrations on each channel and for radial velocity corrections in an electronic computer.

The stellar velocities were obtained by Feast, Thackeray, and Wesselink (1960) with a two-prism Cassegrain spectrograph attached to the 74-in. Radcliffe reflector. Dispersions were 49 and 86 Å/mm at Hγ.

The nebular velocities were measured by Feast (1964) with a grating spectrograph at the Coudé focus of the 74-in. Radcliffe reflector. The dispersion was $15\cdot 6$ Å/mm in the second order.

III. Stellar and HI Radial Velocities

The Feast, Thackeray, and Wesselink (1960) catalogue of the brightest stars in the Magellanic Clouds contains 72 stars of the LMC for which mean radial velocities have been included. These velocities are compared with H-line peak radial velocities in Table 1. The table contains two sections; the stars in group A have radial velocities which fall within the range of velocities covered by the half-width of the corresponding H-line, others are in group B.

The HD or HDE numbers of the stars are listed in the first column of the table, the Radcliffe number in the second, and the right ascension and declination (1963) of the centre of the nearest H-line profile in columns 3 and 4. Radial velocity information is given in columns 5 and 6. The stellar and HI velocities refer to the Sun. $\Delta_{\mathrm{HI}-*}$ in column 7 is the difference in radial velocities (HI$-$stellar). Column 8 lists the half-width of the H-line profile.

Spectral classification of the stars from the Radcliffe table is reproduced in column 9. Finally, the aerial temperature at the H-line profile peak appears in column 10.

Figure 1 shows histograms of $\Delta_{\mathrm{HI}-*}$. The correlation between the velocities in group A is quite striking. The average difference for the 54 stars is $+0\cdot 4$ km/s with standard deviation σ, $\pm 10\cdot 1$ km/s. This σ is very close to the value of the velocity dispersion of $10\cdot 5$ km/s amongst LMC supergiants found by Feast (1964).

The normal distribution curve for $\sigma = 10 \cdot 1$ km/s has been superimposed on the histogram.

The remaining 18 stars in group B have two ranges of radial velocity; 12 are distributed around an average velocity difference Δ_{HI-*} of -35 km/s, 6 around $+34$ km/s. The group B data have been shaded in the diagram.

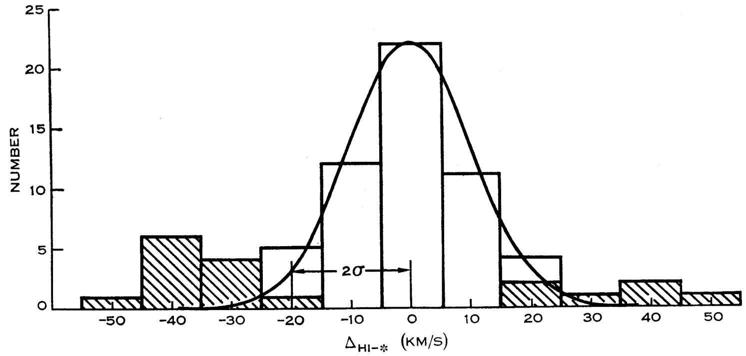

Fig. 1.—Histograms of Δ_{HI-*}, the difference between the HI and the stellar radial velocities. The shaded areas are group B data. A normal distribution curve of $\sigma = 10 \cdot 1$ km/s has been superimposed.

The results in group A suggest that the motions of the stars and the gas must be closely related. Current ideas on the structure of the Large Cloud, based on studies of differential rotation (e.g. Feast 1964; Hindman, Kerr, and McGee 1963) and on the HI observations of the present survey, indicate that this galaxy is a flattened

TABLE 2

COMPARISON OF RESIDUAL RADIAL VELOCITIES FOR "RUN-AWAY" STARS

Radcliffe No.	R71	R76	R78	R118	R122
Residual r.v. (km/s)					
predicted—*	+42	+40	+42	−37	+42
HI—* (from Table 1)	+48	+17†	+4, +46 ‡ (group A)	−46	+41

† Profile complex and very wide.
‡ Two peaks—main body of gas at +284 km/s.

system. It would thus be reasonable to assume that the stars of group A are confined to the "disk" of this system. The stars of group B, with velocities disposed about ± 34 km/s, could well be moving away from the plane in both perpendicular directions.

Further, Feast (1964) has listed five "run-away" stars in the LMC. These are stars whose radial velocities deviate from theoretical values, predicted from a study of the differential rotation, by more than 35 km/s. Comparisons in Table 2 show that, for three of the stars which occur in group B of Table 1, the residuals, on the one hand from the derived differential rotation and on the other from the gas velocities, are of the same order of magnitude. The HI lines in the directions of the other two stars of group A are observed as wide double-peaked profiles in which the nearest peak radial velocities quoted are not true indications for the main body of the gas.

The two groups A and B were examined for relationships with spectral classification, colour excesses, and the HR diagram available from the work of Feast, Thackeray, and Wesselink (1960). In general, no strong correlations were found but a few interesting points have emerged.

(a) *Spectral Classification*

Since all the stars are in the supergiant class, differences in spectral classification with radial velocity distributions could hardly be expected. However, two-thirds of the stars in group B, that is, those with velocities different from the gas, are of spectral types Bo to B5. In group A the proportion of this range is just on one-third.

(b) *Colour Excesses—Reddening*

When the diagram of colours (B−V) *v.* spectral type (Fig. 11 of Feast, Thackeray, and Wesselink 1960) was redrawn in terms of stars from groups A and B of Table 1, the following points were observed.

(1) 17 stars in group A lie close to the intrinsic colour limit from which the amount of reddening is estimated. Their positions are well away from the more densely populated regions of the Cloud. The HI intensities in their directions are relatively low; the average intensity for the 17 is 14°K in aerial temperature compared with the overall average profile peak intensity of 24°K for the whole of group A. Thus we have evidence of low reddening correlating with low gas density.

(2) In the spectral range 05–A3 most of the group B stars of "negative" velocity (with respect to the gas) are less reddened and all the stars of "positive" velocity are more reddened than average.

The study of the gas–stars relationships could be fruitful if many more stellar radial velocities were available. An important region in this respect is the stellar bar of the LMC since the HI survey has shown a comparative lack of gas there (McGee and Milton 1964). Of outstanding interest is the region $05^h\ 42^m$ to $05^h\ 50^m$ in right ascension, −69° to −72° in declination, where double-peaked HI profiles are observed with peak separations from 25 to 70 km/s. If stellar and interstellar radial velocities were obtained in this region, evidence for positioning the two bodies of gas may be forthcoming in a similar manner to that already exploited by Hindman (1964) in an area of the Small Cloud of Magellan.

IV. The Radial Velocities of Ionized and Neutral Hydrogen

The positional agreement between some of the larger regions of ionized hydrogen and concentrations of neutral hydrogen has been pointed out by McGee and Milton (1964). Again, it may be inferred from Feast's (1964) successful use of the nebular radial velocities in the calculation of differential rotation compared with the rotation derived by Hindman, Kerr, and McGee (1963) that HI and HII velocities should be

TABLE 3

HII NEBULAE AND NEUTRAL HYDROGEN

Henize No.	HI Position (1963)		Radial Velocities (km/s)			HI-Line Half-width (km/s)	HI Peak T_A (°K)
	R.A. h m s	Dec. ° ′	HII	HI Peak	Δ_{HI-HII}		
N 4A	04 52 14	−67 00	+292	+292	0	27	43
N 8	04 52 52	−68 12	284	277	−7	26	34
N 11A	04 56 58	−66 24	296	292	−4	30	58
N 11B	04 56 58	−66 24	{303 271	292	−9	30	58
N 11C	04 57 16	−66 36	292	294	+2	34	40
N 17B	05 04 13	−67 24	289	{250 292	+3	32	21
N 44B	05 21 45	−68 00	296	298	+2	24	56
N 44C	05 22 50	−68 00	296	298	+2	27	54
N 55A	05 32 29	−66 24	302	305	+3	15	15
N 57A	05 32 24	−67 48	306	298	−8	18	46
N 72	05 43 44	−66 12	299	307	+8	18	24
N 77A	04 49 21	−69 12	248	256	+8	24	55
N 79B	04 52 27	−69 24	246	256	+10	27	42
N 83A	04 54 01	−69 12	265	258	−7	28	36
N 83B	04 55 11	−69 12	254	258	+4	32	31
N 91A	04 57 42	−68 36	278	278	0	26	29
N 105A	05 10 31	−69 00	256	256	0	25	37
N 113F	05 13 53	−69 24	253	250	−3	22	26
N 117	05 17 30	−69 36	269	248	−21	50	20
N 120A	05 19 48	−69 36	251	258	+7	49	22
N 120C	05 19 48	−69 36	257	258	+1	49	22
N 121	05 19 51	−69 48	243	251	+8	40	15
N 127A	05 22 10	−69 48	259	257	−2	42	19
N 138A	05 25 16	−68 24	276	272	−4	27	49
N 144A	05 27 30	−68 48	264	270	+6	30	12
N 148A	05 33 15	−68 24	272	{277 273	+1	37	50
N 149A	05 33 49	−69 48	276	271	−5	39	18
N 154A	05 35 50	−69 42	268	271	+3	40	34
N 157A	05 39 09	−69 06	260	276	+16	45	53
N 159A	05 39 38	−69 48	252	257	+5	34	67
N 159F	05 39 38	−69 48	254	257	+3	34	67
N 160A	05 40 27	−69 42	246	254	+8	38	71
N 160B	05 40 27	−69 42	254	254	0	38	71
N 160C	05 40 27	−69 42	246	254	+8	38	71
N 168A	05 45 27	−69 48	243	{292 250	+7	32 (est)	35
N 191A	05 04 47	−71 00	242	245	+3	30	15
N 193A	05 13 16	−70 24	247	246	−1	22	29
N 206A	05 31 53	−71 12	240	241	+1	22	47
N213A	05 38 31	−70 42	236	{241 262	+5	56	31
N 214C	05 42 35	−71 24	236	{230 275	−6	34	47
N 218	05 41 27	−70 36	239	243	+4	46	58
N 219	05 42 06	−70 24	242	246	+4	38	61

similar. However, direct evidence is now available which shows a high correlation in the velocities of the 42 nebulae measured by Feast and the neutral gas in the same directions.

In Table 3 the Henize catalogue numbers of the Hα nebulae are given in the first column. The position in right ascension and declination (1963) of the nearest HI observation follows. Columns 4–7 contain the following radial velocity information: the radial velocities of the HII regions, the velocities at the peaks of the HI profiles (referred to the Sun), the differences in these velocities (HI−HII), and the half-widths of the HI profiles. Column 8 lists the intensity of the HI profile peak in degrees Kelvin of aerial temperature.

The average difference ($\overline{\Delta}_{42(\mathrm{HI}-\mathrm{HII})}$) in radial velocity in the 42 cases is $+1\cdot3$ km/s. The standard deviation is only $\pm6\cdot4$ km/s; the correlation coefficient is $0\cdot96$. Feast's (1964) velocity dispersion of the nebulae is $9\cdot3$ km/s.

It would seem that, except for one or two cases, no doubt exists that the ionized gas masses do not possess additional motions to those of the surrounding neutral hydrogen.

V. Conclusion

While difficulties may still exist in the interpretation of relationships between 0-B stars and neutral hydrogen in our own Galaxy, radio and optical observations in the Large Cloud of Magellan present unrivalled opportunities to evaluate the position.

The comparisons of stellar, nebular, and neutral gas radial velocities have produced first-class evidence in support of the usual assumption that stars (young stars at least) and gas share the same motions in a galaxy. The results point the way to more extentive investigations, particularly if the same type of information available from the supergiant observations can be extended to older stars.

VI. Acknowledgments

The author is indebted to Dr. M. W. Feast who made his 1964 manuscript available many months before publication. The criticism and advice of J. G. Bolton is gratefully acknowledged.

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