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Anomalous Motions of H I Clouds

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Summary. In a comparison of H I absorption line velocities and radio recombination line velocities for 38 H II regions of known distance, it is found that the H I absorption extends beyond the recombination line velocity (i.e. corresponds to a greater distance) in the large majority of cases. This is shown to be the result of the overlapping of velocities due to the chaotic motions of two populations of H I clouds. The absorption generally extends all the way to the source and can be used to estimate the velocity corresponding to the distance of the source itself. But it can be misleading if used to resolve the kinematic distance ambiguity when the recombination line velocity is within $\sim$10–20 km s^{-1} of the tangential velocity.

Key words: galactic structure – kinematic distances – H I absorption – interstellar clouds

Introduction

In the idealized picture of our galaxy, cold interstellar clouds like everything else are supposed to move around the galactic centre in circular orbits, their velocities given by the Schmidt model of galactic rotation. This idealized model is used in interpreting H I absorption line velocities in terms of distances – actual distances to the absorbing H I clouds and lower limits for the distances to the background continuum sources.

However, there are non-systematic perturbations superimposed on these circular motions, and their magnitude is not well known. Estimates have been made in a variety of ways, for example by comparing kinematic and photometric distances (Miller, 1968; Georgelin and Georgelin, 1976), or by comparing observed and theoretical tangential velocities at given longitudes (cf. Goss et al., 1972, Table 2). Such methods involve both random motions of the H I clouds and large-scale deviations from the Schmidt rotation model. A more direct measure of the random motions of individual H I clouds is given by a comparison of H I absorption-line velocities with recombination line velocities for H II regions with unambiguous distances. It is such *velocity* differences which are important in using H I absorption lines to resolve the kinematic distance ambiguity, for example. The relevant H I absorption feature in such a case is that whose velocity corresponds to the greatest distance along the line of sight (the extremal velocity).

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A Comparison Between Recombination Line and Extremal H I Absorption Line Velocities

We have examined the difference (ΔV) between the recombination line velocity of the H II region ($V_{\mathrm{Hn\alpha}}$) and the velocity of the extreme H I absorption line feature ($V_{\mathrm{H_I}}$), for those cases where the "most distant" absorbing H I cloud can be unambiguously identified (Table 1). These are cases where the H II regions are strong enough for reliable H I absorption measurements, and where they are located outside the solar circle or very obviously at the near kinematic distance (as indicated by $|V_{\mathrm{TP}}-V_{\mathrm{HI}}|\gg 0$ in Table 1, where V_{TP} is the tangential velocity); the presence of an optical counterpart, and other arguments given in the references for $V_{\mathrm{H_I}}$, provide further support for the choice of these particular H II regions. Figure 1 shows a histogram of the velocity differences ΔV. If there were no non-systematic motions, one would expect only the velocity difference corresponding to the distance between the H II region and the H I cloud immediately in front of it [typically a few hundred parsec, according to Radhakrishnan and Goss (1972)]. This difference would be in the sense that the H I cloud is less distant than the H II region, and its magnitude would depend on the galactic longitude (in some cases the absorbing H I cloud may be physically associated with the H II region, and the velocities might then be expected to be equal). Figure 1 shows, however, that in most (80%) of the cases the velocity of the H I absorption feature corresponds to a *greater* distance than that of the H II region; in these cases the ΔV values shown provide *lower limits* to the real non-systematic motions.

Figure 1 then shows that velocity differences due to non-systematic motions exceed 3 km s^{-1} in half the cases, and 10 km s^{-1} in one case out of six. In four cases the difference is greater than 15 km s^{-1}; there are several other possible examples of large peculiar motions, for example G 316.8–0.1 ($\sim$10–20 km s^{-1} – Shaver et al., 1981), G 10.2–0.3 and G 10.6–0.4 (both $\sim$45 km s^{-1} – Caswell et al., 1975; Greisen and Lockman, 1979), and G 79.3+1.3 ($\sim$40 km s^{-1} – Greisen and Lockman, 1979).

The Random Motions of Interstellar clouds

The histogram in Fig. 1 is striking in three respects; it is highly asymmetric with a relatively sharp lower cutoff, most of the ΔV values (4 out of 5) are positive, and they extend up to 20 km s^{-1} and beyond.

It is difficult to explain these features in terms of peculiar motions of the H II regions themselves. If the only non-systematic motions involved were random motions of the H II regions, one

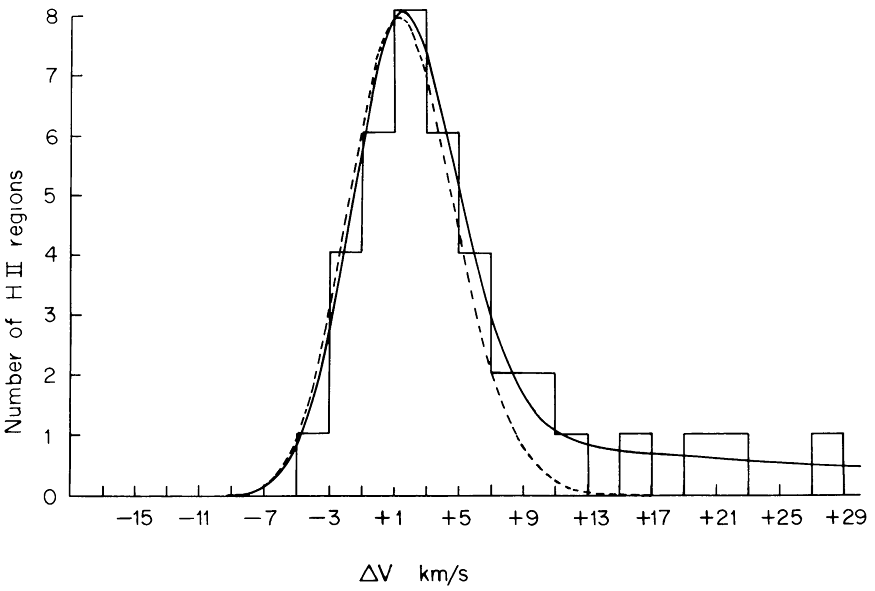

Fig. 1. Histogram of the difference between the H 109α velocity and that of the most extreme H I absorption feature (corresponding to the greatest distance), for 38 galactic H II regions of known distance. ΔV is positive when the H I velocity corresponds to a greater distance than the recombination line velocity, i.e. the absorbing H I cloud appears to be beyond the H II region. The dashed line is the fit obtained by considering the dispersion of the normal clouds. The solid line includes the effect of a small fraction of clouds with much larger anomalous motions (see text)

would expect the histogram to be symmetric, around $\Delta V \lesssim 0$. In particular, there would also be a tail with large negative values of ΔV, corresponding to the positive tail seen in the histogram. Another possibility might be the streaming of the ionized gas of the H II region away from the parent molecular cloud; this would manifest itself as a blue shift of the *visible* H II regions relative to their associated molecular clouds (most of the obscured H II regions should show a corresponding red shift). However, Israel (1978) has shown that the magnitude of such motions is only $\sim 3\,\mathrm{km\,s^{-1}}$ on average. Further, when this is applied as a correction to the velocities of the visible H II regions in Table 1 the average ΔV is increased rather than decreased; most of the visible H II regions in Table 1 are already red-shifted relative to the H I absorption, and their ΔV values show the same asymmetry as the overall sample.

Nor can these features of Fig. 1 be easily explained in terms of large-scale systematic deviations from circular motion, such as density-wave perturbations on the galactic velocity field. Any such interpretations would imply systematic differences in the ΔV values for different quadrants, and these are not evident.

We are thus forced to seek an explanation in terms of chaotic motions of the absorbing H I clouds themselves. Consider N H I clouds along the line of sight to an H II region. Suppose that for each of the clouds the possibility of having a given peculiar motion is given by a (gaussian) probability distribution centred on ΔV_n relative to the H II region. The overall probability distribution for ΔV, the absorption line velocity corresponding to the greatest distance in the direction of the H II region, is then given by

$$P(\Delta V) = \sum_{n=1}^{N} \left[P_n(\Delta V - \Delta V_n) \prod_{m \neq n} \int_{-\infty}^{\Delta V} P_m(\Delta V' - \Delta V_m)\, d\Delta V' \right].$$

It is seen that when the number of clouds N is reduced to one, the distribution is reduced to a simple gaussian with a σ corresponding to the peculiar motion and with a mean corresponding to the position of the cloud, which in velocity is ΔV_n. Let us assume for simplicity that ΔV_n is nearly the same for all the clouds, as would be the case in a direction where the velocity gradient is very small. Now, as the number of clouds is increased, the peak of the curve will shift to more positive values, and an asymmetry will set in making negative velocities less probable and positive velocities more probable. In other words, the order of the clouds in true distance from us will be replaced by the order in most positive peculiar velocities of the various clouds. It should therefore not be surprising if we find that one or two clouds are apparently further than the H II region, providing that we have enough clouds with small values of ΔV_n i.e., with velocities not very different from that of the H II region.

The dashed line in Fig. 1 shows the result of an attempt to make a fit to the histogram on this basis using $\sigma = 4.8\,\mathrm{km\,s^{-1}}$ from a recent determination by Radhakrishnan and Sarma (1980) and assuming $\Delta V_n \approx -3\,\mathrm{km\,s^{-1}}$. The result of a number of attempts seems to indicate that while the position of the peak and the asymmetry on either side can be reasonably accounted for up to a value of $\Delta V \approx +7\,\mathrm{km\,s^{-1}}$, the long positive tail cannot. The histogram can be fitted in its entirety only on the assumption that there is a second population of clouds, which is a fraction of the first, but with a much greater σ. It is interesting that independent evidence indicating the presence of a second population of clouds has in fact been obtained from an investigation of the H I absorption spectrum towards the galactic centre, a direction free in principle of galactic rotation effects (Radhakrishnan and Srinivasan, 1980). In addition to the standard clouds easily seen in absorption and characterized by $\sigma = 4.8\,\mathrm{km\,s^{-1}}$, these authors claim the existence of a large population with σ of $35\,\mathrm{km\,s^{-1}}$ but with much lower optical depths. These clouds can be detected only in directions where their velocities do not overlap those of the denser clouds and blend with them. They are thus seen in the direction of the galactic centre where $dV/dR = 0$, and also at high latitudes in sufficiently sensitive surveys (Dickey et al., 1978).

A region in velocity space where such blending cannot occur, or is very unlikely, is in absorption spectra at velocities beyond those reachable by the normal population. In other words, the portion of the histogram in Fig. 1 with large positive values of ΔV is precisely what is required to notice the presence of such clouds, given sufficient optical depth to be detectable. Because of their large σ, they can overreach the velocity of the H II region and appear to be more distant. Again because of the large dispersion one has a much greater stretch in which to find such a cloud before ΔV_n for this cloud becomes comparable to its $\sigma \approx 35\,\mathrm{km\,s^{-1}}$.

The mean optical depth of these clouds which are numerous has been estimated to be below 0.3 (Radhakrishnan and Srinivasan, 1980); but they must really form a distribution with a finite probabil-

Table 1. A comparison of recombination line and maximum H I absorption line velocities

Source G	Source Optical	$\|V_{TP}-V_{HI}\|$ (km s^{-1})	$V_{Hn\alpha}$ (km s^{-1})	Ref.	V_{HI} (km s^{-1})	Ref.	ΔV[a] (km s^{-1})
206.5 − 16.4	NGC 2024	[b]	+ 6.0	4	+ 9.7	1	+ 3.7
209.0 − 19.4	Orion	[c]	− 2.8	4	+ 5.5	1	+ 8.3
243.1 + 0.4	RCW 16	[b]	+52.6	6	+54	3	+ 1.4
265.1 + 1.5	RCW 36	[b]	+ 2.8	4	+ 4.8	1	+ 2.0
268.0 − 1.1	RCW 38	[b]	+ 1.8	4	+ 7.1	1	+ 5.3
274.0 − 1.1	RCW 42	[b]	+39	7	+36	3	− 3
282.0 − 1.2		[b]	+22.4	4	∼ +20	2	− 2.4
284.3 − 0.3	RCW 49	[b]	− 0.7	4	∼ + 4	2	+ 4.7
298.2 − 0.3		[b]	+30.6	4	∼ +28	2	− 2.4
298.9 − 0.4		[b]	+24.2	4	∼ +25	2	+ 0.8
322.2 + 0.6	RCW 92	30	−51.8	4	−56	3	+ 4.2
326.6 + 0.6	Nebulosity	48	−44.5	4	∼ −47	2	+ 2.5
327.3 − 0.6	RCW 97	46	−48.8	4	−49.5	2	+ 0.7
330.9 − 0.4		41	−56.1	4	−63	3	+ 6.9
332.2 − 0.4		50	−55.0	4	−56	3	+ 1
333.1 − 0.4		52	−55.8	4	−54.9	2	− 0.9
333.6 − 0.2	Nebulosity	38	−48.3	4	−70	3	+21.7
336.5 − 1.5	RCW 108	87	−24.9	4	−26	3	+ 1.1
337.9 − 0.5		55	−40.4	4	∼ −60	3	+19.6
338.9 + 0.6		55	−63.0	4	−62	3	− 1
340.8 − 1.0	RCW 110	92	−24.8	4	−28	3	+ 3.2
345.4 − 0.9	RCW 117	96	−23.5	6	−34	1, 3	+10.5
345.4 + 1.4	Nebulosity	106	−14.6	4	−24	3	+ 9.4
348.7 − 1.0	RCW 122	99	−12.8	4	−40.0	1	+27.2
351.4 + 0.7	NGC 6334	151	− 3.2	4	− 5.0	1	+ 1.8
351.7 − 1.2		129	−12.2	5	−28.7	1	+16.5
353.1 + 0.7	NGC 6357	162	− 4.1	4	∼ − 5	1	+ 0.9
353.2 + 0.9	NGC 6357	157	− 3.8	4	∼ −11	1	+ 7.2
6.0 − 1.2	M8	158	+ 3.0	5	+15.4	1	+12.4
12.8 − 0.2		98	+36.3	5	+36.3	1	0.0
15.0 − 0.7	M17	106	+18.4	4	∼ +23	1	+ 4.6
16.9 + 0.7	M16	105	+24.5	5	+19.5	1	− 5.0
25.4 − 0.2		44	+60.4	5	+66.4	1	+ 6.0
28.8 + 3.5	RCW 174	97	+ 0.7	5	+ 7.2	1	+ 6.5
30.8 − 0.0		[c]	+92.7	4	+97.6	1	+ 4.9
34.3 + 0.1		37	+53.9	5	+56	3	+ 2.1
35.2 − 1.8		47	+46.5	5	+44.3	1	− 2.2
111.5 + 0.8	S158	[b]	−60.6	5	−62	8	+ 1.4

[a] ΔV is positive when the H I velocity corresponds to a greater distance than that of the $Hn\alpha$

[b] Source lies outside solar circle

[c] See Radhakrishnan et al. (1972)

References

1. Radhakrishnan et al. (1972)
2. Goss et al. (1972)
3. Caswell et al. (1975)
4. Wilson et al. (1970)
5. Reifenstein et al. (1970)
6. Shaver et al. (1982)
7. Caswell (1972)
8. Greisen and Lockman (1979)

ity of finding a few with higher optical depths detectable in the surveys from which the data of Fig. 1 is taken. We have indicated by the full line in Fig. 1 a fit to the histogram obtained by adding one cloud with $\sigma = 35$ km s^{-1} to four with $\sigma = 4.8$ km s^{-1}. The ΔV_n for the "high σ" cloud has been taken to be -15 km s^{-1} corresponding to an average distance from the H II region of the order of 1.5 kpc. Equally satisfactory fits can be obtained by using smaller values of σ with correspondingly smaller values of ΔV_n for the cloud of the second population. In the extreme case where ΔV_n approaches zero, σ for this second population approaches 15 km s^{-1}. We conclude that the effective dispersion for the second population to needed to explain this histogram is at least 15 km s^{-1}, or three times that assumed for the standard population.

If the satisfactory fit to the histogram can be taken as supporting our interpretation, then we should also expect to find a correlation of optical depth with ΔV. On the other hand, with only the standard population of clouds, these two quantities would be expected to be totally independent and unrelated. The mean value of the optical depth of the features with $\Delta V > 7.5\ \mathrm{km\ s^{-1}}$ is 0.77 whereas the corresponding value for $\Delta V < 7.5\ \mathrm{km\ s^{-1}}$ is 2.14. While this certainly supports our hypothesis, it should be cautioned that the greater blending at lower values of ΔV will tend to suggest such a correlation even with a single population.

H I Absorption Measurements and Kinematic Distances

The results presented above have interesting implications for the determination of distances using H I absorption line measurements. Radhakrishnan et al. (1972) and Caswell et al. (1975) have argued that H I absorption is generally found all the way to the source, and that distances based on H I absorption measurements are therefore more than mere lower limits. Figure 1 not only demonstrates this but goes much further. The average value of ΔV from Table 1 is $+4.8\ \mathrm{km\ s^{-1}}$, and the median is $+3.0\ \mathrm{km\ s^{-1}}$; the standard deviation is $\sim 7\ \mathrm{km\ s^{-1}}$. On average, therefore, H I absorption extends out to $\sim 5 \pm 7\ \mathrm{km\ s^{-1}}$ *beyond* the velocity appropriate to the source itself. This fact can be used in estimating the actual distance of the source, subject to the further uncertainties in the appricability of the Schmidt rotation model to the large-scale velocity field of the galaxy.

These results are also important in connection with the use of H I absorption measurements to resolve the kinematic distance ambiguity. It is generally assumed that when absorption extends beyond the recombination line velocity and approaches the tangential velocity, the H II region must be at the far kinematic distance. It is clear from Fig. 1, however, that the absorption velocity exceeds the recombination line velocity in the majority of cases; the difference is greater than $10\ \mathrm{km\ s^{-1}}$ in one case of six. This method for resolving the distance ambiguity may therefore be misleading when the recombination line velocity is within ~ 10–$20\ \mathrm{km\ s^{-1}}$ of the tangential velocity. As discussed in the previous section, such a situation is particularly favourable for the overlapping of the velocity distributions.

The simple analysis in this paper was aimed at showing that the unexpected distribution of ΔV in Fig. 1 is in fact a perfectly reasonable consequence of the anomalous motions of interstellar clouds; also to point out its implications for distance determinations as discussed above. A more rigorous analysis taking into account the heterogeneous nature of the sample obtained in directions with different velocity gradients is presently in progress. The result of this analysis to be published elsewhere is expected to yield as an independent determination the number densities and the dispersions of the two cloud populations which were assumed in the present case.

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