The DDO IVC Distance Project

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Abstract. We present the first set of distance limits from the David Dunlap Observatory Intermediate Velocity Cloud (DDO IVC) distance project. Such distance measures are crucial to understanding the origins and dynamics of IVCs, as the distances set most of the basic physical parameters for the clouds. Currently there are very few IVCs with reliably known distances. This paper describes in some detail the basic techniques used to measure distances, with particular emphasis on the the analysis of interstellar absorption line data, which forms the basis of our distance determinations. As an example, we provide a detailed description of our distance determination for the Draco Cloud. Preliminary distance limits for a total of eleven clouds are provided.

1. Introduction

Since their discovery in 1963 by Muller, Oort & Raimond, the high- and intermediate-velocity clouds (HVCs and IVCs respectively) have been somewhat of a mystery. Central to our lack of understanding of these discrete clouds is our lack of knowledge of their distances. The distances set many of the basic physical parameters of the clouds (see Table 1) and are critical in interpreting origin and evolution models for these objects (see Wakker and van Woerden 1997 - hereafter WvW97 - for a review of models). Furthermore, both the IVCs and HVCs show significant correlations with Galactic x-ray emission (e.g. Snowden et al. 1991, Kerp et al. 1998, Gladders et al. 1998) and knowledge of the distances to these clouds helps to constrain models of the x-ray emitting gas in the Galaxy. The HVCs have received significant observational attention in recent years, and distance limits have now been set to several large HVC complexes (WvW97). A similar concerted effort has not occurred in determining distances for the IVCs, and distance limits have been set for only a few IVCs.

Several methods have been used for determining HVC and IVC distances. The most direct and convincing of these is the absorption line method (e.g. Lilienthal et al. 1991, Benjamin et al. 1996). The basic technique is to obtain relatively high resolution spectra of probes (typically, early-type stars) along the line-of-sight to the target cloud, searching for interstellar absorption from appropriate
metallic species at the cloud’s systemic velocity. Any star showing such absorption can then be considered to be behind the cloud, and any star not showing such absorption (modulo covering factor effects - see Burns et al. 1999) to be in front of the cloud. Distance estimates to the bracketing stars, typically determined from spectroscopic parallax, then provide a distance bracket for the cloud. The primary drawback to this approach is that it requires a large investment of telescope time, as the search for stars showing the expected absorption may require data on numerous potential background sources. Moreover, in the absence of detected absorption, the interpretation of non-detections of absorption is somewhat ambiguous (WvW97).

An ongoing project has been started at the David Dunlap Observatory (DDO) to address the lack of distance measures to IVCs via the absorption line technique. The primary goal of this project is to obtain both upper and lower distance estimates for a significant sample of IVCs. The potential astrophysical applications of this work are described elsewhere (Clarke et al. 1998); in this paper we concentrate on a thorough description of our methodology, and give some first results. §2 describes our target selection process, observations and data reduction techniques. §3 describes our analysis procedures, both for the detection/non-detection of cloud-induced interstellar absorption and our spectroscopic classification and resulting distance measures for useful bracketing stars. §4 gives preliminary distances for a total of 11 IVCs.

### Table 1. The dependence of some physical parameters of IVCs on the cloud distance (WvW97).

| Parameter       | Exponent |
|-----------------|----------|
| Column Density  | d^0      |
| Density         | d^{-1}   |
| Linear Size     | d^{+1}   |
| Mass            | d^{+2}   |
| Metallicity     | d^0      |
| Pressure        | d^{-1}   |

2. Target Selection and Observations

2.1. Cloud Targets

The primary cloud sample we have been observing is drawn from the IVC sample of Heiles, Reach and Koo (1988; hereafter HRK88). These clouds were selected primarily on the basis of their *IRAS* 100µ emission, and form a relatively homogeneous set of isolated interstellar clouds. Each cloud is ~ 1° in size, and most are at high galactic latitudes. From the HRK88 sample of 26 clouds, we have selected a subset of 16 clouds, all readily observed from the DDO. Of these, we have eliminated G137.3+53.9 and G135.3+54.5 (the UMa IVC) from our sample, as these two poorly separated clouds already have a measured dis-
distance (Benjamin et al. 1996). We have retained the nearby cloud G135.5+51.3 (considered by Benjamin et al. to be part of the UMa Cloud) as examination of the HI atlas of Hartmann and Burton (1997) indicates that this cloud may be a separate object. Conversely, we have combined three pairs of clouds from the HRK88 sample, due both to their apparent lack of separation on the sky (in both HI and IRAS 100µ emission) and their lack of separation in velocity space (HRK88). The final cloud sample thus contains eleven clouds (Table 2).

2.2. Stellar Targets

The primary catalog of potential stellar probes we have used is the Tycho catalog (Hog et al. 1997), occasionally supplemented by the USNO catalog. The Tycho catalog provides positions and $B-V$ colours for over one million stars covering the entire sky. The sample is complete to $V \sim 11$, and contains stars to $V \sim 12$. At the completeness limit, the accuracy of the $B-V$ colours from the catalog is $\sim 0.1$, more than sufficient to give a rough indication of the spectral class of each star. Some knowledge of the spectral class of potential target stars is required, as this can be used to provide a rough estimate of the distance to each star. Furthermore, the interstellar absorption line method requires stars of relatively early spectral type, as these stars provide a relatively clean stellar continuum against which interstellar absorption is readily identified.

Our stellar target selection process for a given cloud proceeds as follows. First, we delineate a bounding contour for the cloud in HI, using the HI maps of Hartmann and Burton (1997). This boundary is selected from an $\ell, b$ map of a velocity slice $\pm 5 \text{ km s}^{-1}$ about the cloud’s systemic velocity as given by HRK88. The boundary is set at a flux level which clearly delineates the cloud relative to the background. We then select all stars from the Tycho catalog which lie interior to this boundary, and which have a blue colour ($B-V < 0.4$). Such stars are likely to be early type stars with spectral classes earlier than F5, although the large colour errors in the Tycho catalog at the flux limits of the sample do cause some contamination by later-type stars. We then produce an HI spectrum and a nominal distance estimate for each star. The distance estimate is made by assigning a spectral class based on colour and assuming the star is a main-sequence dwarf, thus assigning an absolute magnitude to each star. This distance estimate may be quite uncertain, due to large colour errors (see §4 for more details). A subset of these potential target stars is then selected on the basis of distance and HI column due to the cloud. This subset is then placed in our observing queue and observed as conditions dictate.

2.3. Observations

All the observations undertaken for this project have been made with the DDO 1.88m telescope + Cassegrain spectrograph. A total of 84 nights have been assigned to this project since May 1997, of which 59 nights have produced at least some useful spectroscopic observations. These spectroscopic observations are of two flavors - moderate resolution spectra at the Na I doublet (to search for interstellar absorption) and lower resolution ‘classification spectra’ (to refine our stellar spectral classifications). Each type of observation and any supplementary observations of each type are described in detail below.
Interstellar Absorption  The interstellar absorption spectra have all been acquired using the DDO Cassegrain spectrograph at its finest possible resolution, corresponding to a velocity resolution of 22 km s\(^{-1}\) at the Na I doublet. This resolution is coarser than used by other authors (e.g. Benjamin et al. 1996), but is sufficient to detect (though not resolve) the absorption features due to IVCs. We have observed stars to a limiting magnitude of \(V \sim 12.5\); on such targets we achieve a S/N of 50 in 4 hours. Target stars are observed as conditions dictate, with the faintest targets reserved for the best conditions. We also observe several telluric standards repeatedly during each night. Numerous telluric standards have been observed in the course of this project, and we have found only two stars (HD177724 and HD120315) which are not polluted by low-velocity interstellar Na I absorption. These two stars are the primary telluric standards used for all data (see Figure 1). We have also obtained spectra of numerous spectral classification standards with the Na I setup, to provide the necessary input into our analysis techniques (see §3.1).

![Figure 1. A typical telluric spectrum of HD177724, in arbitrary intensity units. As mentioned in the text, only HD177724 and HD120315 have been used as telluric standards, as all other tellurics observed showed significant low-velocity Na I absorption.](image)

Spectral Classification  The spectral classification setup used covers a spectral range of 3800-4400 Å, with a resolution of 2.5 Å. Classification spectra have been acquired after the sodium observations, for only a subset of all stars observed at the Na I doublet. We have not taken classification spectra of target stars prior to the acquisition of sodium spectra because the spectrograph used is very inefficient in the blue, mandating roughly equal total integration times for both spectra. This makes the pre-selection of distant targets through spectral classification no more efficient than direct observations of likely targets identified.
by colour. We have also acquired spectra of a suite of spectral classification standards (taken from Garcia 1989), ranging in spectral type from B0 to G5, and spanning luminosity classes I-V.

Figure 2. The sky spectrum at DDO from 5700-6100 Å, in arbitrary intensity units. Note the broad emission from high-pressure sodium lamps, which is strongly self absorbed at the doublet wavelengths. The most troublesome features of the sky spectra are the sharp emission lines due to low pressure sodium lamps. Correct subtraction of these lines is essential.

2.4. Data Reduction Techniques

The reduction of both types of spectral data is accomplished via a data-reduction pipeline, implemented under IRAF\(^1\). The data reduction follows relatively standard longslit spectral reduction procedures, and will not be described in great detail here. Two things should be noted, however. First, the data are usually processed to telluric corrected, wavelength calibrated, heliocentrically corrected 1-D spectra within 24 hours of acquisition. This rapid processing allows us to use recent observations of a given cloud to guide the selection of other target stars. Second, great care is given to the subtraction of sky-lines in the Na I doublet spectra, as DDO’s close proximity to Toronto makes it a highly light-polluted site. Luckily, most of the sodium lights near DDO are high pressure lamps, which are strongly self absorbed at the doublet wavelengths, with only a small contribution from low-pressure lamps (see Figure 2).

\(^1\)IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.
3. Analysis Techniques

The analysis of the spectroscopic data can be roughly divided into three parts, each of which is described in some detail below. The first is the identification of detections and non-detections of interstellar absorption in the Na I spectra. The second is the assignment of each star to either the foreground or background relative to the cloud. Though the background identifications are simple once an absorption detection is made, the unambiguous identification of a star as a foreground object is non-trivial and subject to several uncertainties. The third step in the analysis is to assign a distance to each foreground and background star via spectroscopic parallax, and hence produce a distance bracket to the target cloud.

3.1. Detections of Interstellar Absorption

The correct identification of absorption due to the target IVC is one of the critical steps in our analysis. The most significant sources of confusion are intrinsic stellar lines mis-identified as interstellar features. Unlike other authors (e.g. Benjamin et al. 1996), we have used somewhat later type stars in our target sample, and so must be more concerned about possible contamination by stellar sodium lines. Furthermore, our spectra are not of sufficient resolution to resolve the interstellar absorption features expected from the target IVCs (HRK88), and so we cannot rely upon the line profiles as an indicator of the origin of observed sodium absorption lines. However, the use of only moderate dispersion does provide a significant gain in the wavelength sampling of the underlying stellar spectrum, and we use this fact to motivate our analysis. For any sodium spectrum, the analysis proceeds as follows.

First, we make a rough estimate of the spectral class of the star using the sodium spectrum itself (or, if available, a classification spectrum - see §3.3). We then select a matching standard star from our database of standards and measure the equivalent width and central wavelength of all significant features in this standard spectrum. These measurements are used to construct a synthetic spectrum; the synthetic spectrum has a flat continuum, with sharp (FWHM << spectral resolution in real spectra) absorption features with equivalent widths consistent with the standard at $V_{LSR} = 0$ (Figure 3).

Next, we cross-correlate this synthetic spectrum with the target spectrum in two regions. The first cross-correlation is performed only in the ‘stellar’ region of the spectrum. This is essentially all of the input spectrum except the Na I doublet region. The resulting cross-correlation gives the radial velocity and width of the stellar features. The second cross-correlation is performed only in the Na I doublet region, and gives the radial velocity and width of the stellar features and interstellar features. A simple comparison of the two cross-correlations then determines which, if any, Na I features can be attributed to interstellar absorption. Figure 4 details this process for a star for which the interstellar absorption component attributed to the intervening IVC is clearly distinguished, despite serious contamination by stellar sodium features at essentially the same radial velocity.
Figure 3. An example of a synthetic spectrum constructed from a standard star spectrum, in arbitrary intensity units. The input spectrum, for the F6V star HD173667, is shown at the top, and the resulting synthetic spectrum, not at the same scale, is shown below it.

3.2. Foreground and Background Stars

The identification of detections and non-detections is only the first step in determining the placement of stars in relation to the target IVC. Critical to the distance determination process is the correlation between non-detections (at a given significance) and foreground objects. There are several reasons why this is non-trivial. First, stellar probes provide a pencil beam for the detection of Na I absorption, which is then compared to a much larger beam from HI data. At smaller scales than the HI data the clouds may have a covering factor which is significantly less than unity, which could produce non-detections for stars which are behind the target cloud. Second, in the absence of detections of Na I absorption due to the cloud, the metallicity of the cloud remains uncertain, and so the expected Na I equivalent width given a HI column density is uncertain, quite apart from small-scale covering factor effects. The problem of metallicity is easily addressed; all non-detections are to a degree ambiguous without at least one detection to set the HI/Na I ratio. Of course, one can extrapolate the expected HI/Na I ratio from other clouds in the same sample, assuming the ratio is constant. In the absence of further data, this is a reasonable approach. Notably, the cloud sample we are observing is large enough to directly test this
The cross-correlation results for TYC 4152 484 1. The dotted line shows the cross-correlation for the 'stellar region', and the solid line for the sodium region. Note that the broad stellar peak is represented in the sodium peak, as expected, but that the additional sharp component in the sodium cross-correlation shows no corresponding stellar feature. This peak, at $V_{LSR} \sim -12$ km s$^{-1}$, is due to the IVC G139.6+47.6.

assumption. The problem of small-scale structure is more difficult to surmount. One possible approach is to compare the relationship between detections of Na I absorption and distance for a sample of stars towards a single cloud in which more than a single detection and non-detection have been made. For one cloud in our sample (G139.6+47.6 + G141.1+48.0) we have observed a total of 20 stars, and made 8 detections. A preliminary analysis of these data indicate a one-to-one correspondence between detection of absorption and distance, in that the eight stars showing absorption are also the eight most distant. A full treatment of these data will be presented elsewhere (Burns et al. 1999), but the preliminary indication is that the small scale covering factor is near unity.

Armed with this conclusion, we now proceed as follows in determining the placement of target stars relative to a given cloud. First, the detected absorption is used to set the HI/Na I ratio for the cloud. In the absence of detected absorption, the mean observed for other clouds is used. We then extract HI spectra towards each target star from the HI data of Hartmann & Burton (1997) and measure the HI column density due to the cloud along each line of sight. These data are then used to predict an expected Na I equivalent width for each star, assuming that the stars are behind the target cloud. The predicted Na I absorption can then be compared to the observed spectra, which are nom-
inally non-detections of absorption. In each case, the expected absorption must be compared to the sensitivity of each spectrum; in cases where the expected absorption may be lost in the noise, the stars must either be discarded from the sample, or re-observed to resolve the ambiguity. Only stars in which the expected absorption is clearly un-detected can be taken as foreground stars. Figure 5 demonstrates this analysis for four stars towards the Draco Cloud (G90.0+38.8 + G94.8+37.6).

![Figure 5](image-url)

Figure 5. Na I spectra for four stars towards the Draco Cloud, from Gladders et al. (1998). Measured spectra are shown as thick lines. The topmost spectrum (TYC 4194 2188) shows absorption due to the Draco Cloud. This has been used to predict the expected absorption in the other three spectra, as described in the text, and shown as thin lines. Of the three remaining spectra, only the bottom two clearly correspond to foreground stars. The other spectrum (BD+64 1134) is ambiguous, as the expected absorption is small enough that it could simply be undetected in these data.

3.3. Distances

All useful stars (i.e. those with unambiguous identifications as either foreground or background stars) with classification spectra have been classified by comparison to the observed set of spectral standards. The derived spectral class and the absolute magnitude calibration of Corbally & Garrison (1984) were then used to assign an absolute magnitude, and hence distance, to each star. We have considered three sources of error in this distance estimate: 1) the error in the Tycho V magnitude; 2) an assumed classification error of ± one spectral class for each star; 3) the intrinsic dispersion (0.7 mag) in the absolute magnitude relation vs. MK spectral class (Jaschek & Gómez 1998). We have not accounted for extinction, as the expected overall extinction along typical lines of sight at these galactic latitudes is small. However, we do expect some extinction of the background stars due to the intervening IVCs, particularly because these IVCs are
known to be somewhat dusty (HRK88). However, without detailed multi-band photometry of these stars, the degree of extinction is unknown, though likely quite small (Stark et al. 1997). Note that the inclusion of extinction can only reduce the estimated upper distance limits. Given that we now have a spectroscopically identified sample of background stars, we plan to gather the necessary data to resolve the extinction problem. In the absence of that data however, we conservatively include no extinction when estimating distances.

For some IVCs classification spectra of some stars have not yet been acquired. In these cases we have tentatively estimated the distance by assigning a spectral class on the basis of the $B - V$ colour from the Tycho catalog. In such cases the distance estimates are often quite uncertain, as we assign errors to the distance based on the uncertainty in the colour.

4. Preliminary Distance Results and Conclusions

The preliminary distance limits for the our entire target sample of 11 clouds is given in Table 2. While it is apparent that much remains to be done to refine these measurements, the current data do set some interesting limits on the distances for these IVCs. In general, all are more distant than 200pc, and some may be up to several kiloparsecs distant. Given that all the clouds are at significant Galactic latitudes, this implies that the bulk of these IVCs are not in the gaseous disk, but falling in towards it. The DDO IVC distance project is a continuing effort, and we anticipate refining these distance estimates in the near future. Moreover, we expect to add many more IVCs to our sample in an attempt to refine the statistical picture for these interesting objects.

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References

Benjamin, R.A., Venn, K.A., Hiltgen, D.D., Sneden, C. 1996, ApJ, 464, 836
Burns, C.R. et al. 1999, in preparation
Clarke, T.E., Mallen-Ornelas, G., Sawicki, M., Gladders, M.D., Burns, C.R., Attard, A. 1998, in New Perspectives on the Interstellar Medium, eds. A.R. Taylor, T.L. Landecker and G. Joncas, ASP Conference Proceedings, in press [astro-ph/9811066]
Corbally, C.J., Garrison, R.F. 1984, in The MK Process and Stellar Classification, ed. R.F. Garrison, (toronto: DDO), 277
Garcia, B. 1989, Bull. Inf. Cent. de Donnees de Strasbourg, 36, 27 Gladders, M.D., Clarke, T.E., Burns, C.R., Attard, A., Casey, M.P., Hamilton, D.,
| Cloud(s)            | $V_{LSR}$ (km s$^{-1}$) | Distance Limits (pc) | # Det's | # Stars |
|---------------------|-------------------------|----------------------|---------|---------|
|                     |                         | Lower                | Upper   |         |
| G163.9+59.7         | -19.0                   | $543_{-243}^{+514}$  | $1537_{-541}^{+844}$ | 1 / 5   |
| G139.6+47.6,G141.1+48.0 | -12.1,-12.9            | 233_{-116}^{+492}   | 325_{-66}^{+403}    | 8 / 20  |
| G135.5+51.3         | -47.2                   | $746_{-433}^{+1747}$ | 1419_{-362}^{+485}  | 1 / 3   |
| G149.9+67.4         | -6.3                    | $372_{-113}^{+123}$  | $545_{-82}^{+110}$  | 1 / 3   |
| G249.0+73.7         | -0.6                    | $226_{-48}^{+75}$    | –       | 0 / 1   |
| G124.1+71.6         | -11.4                   | $252_{-16}^{+17}$    | $843_{-396}^{+1181}$| 1 / 2   |
| G107.4+70.9,G99.3+69.0 | -29.9,-26.6            | 742_{-217}^{+324}   | 823_{-251}^{+393}   | 1 / 8   |
| G86.5+59.6          | -39.0                   | $604_{-178}^{+237}$  | –       | 0 / 10  |
| G90.0+38.8,G94.8+37.6 | -23.9,-23.3            | 463_{-136}^{+192}   | 618_{-174}^{+243}   | 1 / 8   |
| G81.2+39.2          | +3.5                    | 450_{-132}^{+187}   | 851_{-276}^{+407}   | 2 / 5   |
| G86.0+38.3          | -43.4                   | $921_{-280}^{+443}$  | $2366_{-795}^{+1192}$| 1 / 7   |

Table 2. The preliminary distance results for the DDO IVC distance project. Both upper and lower distance limits are given for 9 clouds, with only lower limits for 2 clouds. Errors for each distance limit are given, computed as described in the main text. Distance limits given in italics are from distances based only on $B-V$ colours.

Mallen-Ornelas, G., Karr, J.L., Poirier, S.M., Sawicki, M., Barrientos, L.F. and Mochnacki, S.M. 1998, ApJ, 507, 161
Hartmann, D., Burton, W.B. 1997, Atlas of Galactic Neutral Hydrogen, Cambridge Univ. Press, Cambridge, U.K.
Heiles, C., Reach, W.T., Koo, B. 1988, ApJ, 332, 313 (HRK88)
Hog, E., Baessgen G., Bastian, U., Egret, D., Fabricius, C., Grossman, V., Halbwachs, J.L., Makarov, V.V., Perryman, M.A.C, Schwenkendiek, P., Wagner, K., Wicenec, A. 1997, A&A, 323, 57
Jaschek, C., Gómez, A.E. 1996, A&A, 330, 619
Kerp, J., Pietz, J., Kalberla, P.M.W., Burton, W. B., Egger, R., Freyberg, M. J., Hartmann, D., Mebold, U. 1998, in The Local Bubble and Beyond, eds. D. Breitschwerdt, M. J. Freyberg, and J. Truemper, IAU Conference Series vol. 506, (Springer-Verlag: Berlin), 457
Lilienthal, D., Wennmacher, A., Herbstmeier, U., Mebold, U. 1991, A&A, 250, 150
Muller, C.A., Oort, J.H., Raimond, E. 1963, C.R. Acad. Sci. Paris, 257, 1661
Snowden, S. L., Mebold, U., Hirth, W., Herbstmeier, U., Schmitt, J. H. M. M. 1991, Science, 252, 1529
Stark, R., Kalberla, P., Güsten, R. 1997, A&A, 317, 907
Wakker, B.P., van Woerden, H. 1997, ARA&A, 53, 217 (WvW97)