The Distance to the Draco Cloud

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ABSTRACT

The understanding of the nature of intermediate and high velocity gas in the Milky Way is hampered by a paucity of distance estimates to individual clouds. A project has been started at the David Dunlap Observatory to address this lack of distance measures by observing early-type stars along the line of sight towards these clouds and searching for sodium doublet absorption at the clouds' systemic velocities. Distances to foreground stars (no absorption) and background stars (with absorption) are estimated from spectroscopic parallax, and thus the distance to the bracketed cloud is estimated. In this Letter, we present the first result from this ongoing project, a measurement of the distance to the Draco Cloud, which is the most studied of the intermediate velocity clouds. The result presented here is the first distance bracket which tightly constrains the position of the Draco Cloud. We briefly describe our target selection and observing methodology, and then demonstrate absorption at the velocity of the Draco Cloud for one star (TYC 4194 2188), and a lack of absorption for several other stars. We derive a distance bracket to the Draco Cloud of $463^{+192}_{-136}$ to $618^{+243}_{-174}$ pc.

Subject headings: ISM: clouds — ISM: individual (Draco Cloud) — ISM: structure — stars: distances — X-rays: ISM
1. INTRODUCTION

Observations in the 21cm HI line reveal the presence of discrete clouds of neutral hydrogen at high galactic latitudes (e.g. Hartmann & Burton 1997). These clouds, whose velocities cannot be explained by differential galactic rotation, are generally grouped into velocity subsets based on their radial velocities relative to the local standard of rest (LSR). Historically, the clouds with \(|V_{LSR}| > 70 \text{ km s}^{-1}\) are labeled high-velocity clouds (HVCs) and those with \(|V_{LSR}| < 70 \text{ km s}^{-1}\) are termed intermediate-velocity clouds (IVCs). Recent indications from both dust surveys and distance estimates suggest that the two classes are indeed distinct populations (Burton 1996).

The distances to the clouds are necessary to constrain the most significant physical parameters, such as mass, size, density and pressure. Without distance information, the origins of these clouds remains speculative. Numerous origin scenarios have been proposed, including Local-Group infall from the intergalactic medium (Blitz et al. 1998), products of thermal instabilities acting at large scale heights in the galactic halo, and cooled infalling gas which was ejected into the halo from energetic disk events (see review by Wakker & van Woerden 1997). It is essential to determine the cloud distances in order to distinguish between such scenarios.

Cloud distances are also fundamental to understanding the soft X-ray background (SXRB). For example, SXRB measurements in the direction of the Draco Cloud show a reduction of \(\sim 50\%\) in the 0.25 keV emission over the cloud relative to the adjacent sky (Burrows & Mendenhall 1991; Snowden et al. 1991). This depression is consistent with photoelectric absorption of the SXRB emission by the cloud. The nature of the SXRB is uncertain. One model suggests that most of the SXRB arises from local low-density plasma (Saunders et al. 1977). This Local Hot Bubble (LHB) has a temperature of \(\sim 10^8 \text{ K}\) and extends for a few hundred parsecs. Other models propose that the majority of the SXRB emission originates at large distances in the Galactic halo (e.g. Marshall and Clark 1984). Again, in order to distinguish between models, it is essential to determine the distances to the shadowing clouds.

The Draco Cloud (\(\ell=90^\circ.0, b=38^\circ.8\)) is the best studied of the high-latitude IVCs (e.g. Lilienthal et al. 1991 and references therein), but its distance is still uncertain. Two different upper distance limits have been suggested by: 1) star count measurements (Rohlfs 1986: 2000 pc) and 2) differential star count measurements (Wenmacher 1988: 1500 pc). Three different lower distance limits have been suggested by: 1) \(UBV\) photometry (Goerigk & Mebold 1986: 800 pc), 2) star count measurements (Mebold et al. 1985: 800 pc) and 3) interstellar absorption-line measurements (Lilienthal et al. 1991: 300 pc). Notably, the limits from star count data and \(UBV\) photometry may require significant revision, as recent work by Stark et al. (1997) indicates that the extinction due to the Draco Cloud may have been overestimated by a factor of four or more. Of all methods used, the most promising is interstellar absorption line measurements, both in terms of the potential accuracy of the derived distance, and the insensitivity to systematic errors (Wakker & van Woerden 1997).

In this Letter, we derive a distance to the Draco Cloud using the interstellar absorption-line technique. This distance estimate is based on moderate-resolution spectra at the sodium doublet of four stars in the line of sight to this cloud. One star clearly displays interstellar absorption at the systemic velocity of the Draco Cloud and is thus behind it. The three other stars show no interstellar absorption, and are thus in front of it. From spectral classifications, we deduce a distance to each star, and hence bracket the cloud distance. This represents the first measurement of the distance to the Draco Cloud where both firm upper and lower limits can be given. In §2 we describe the target selection process, observations and data reduction. In §3 we demonstrate the interstellar absorption in the background star, and the lack of interstellar absorption in the foreground stars. The distance to the Draco Cloud is derived in §4.

2. OBSERVATIONS

Numerous stars along the line-of-sight towards the Draco Cloud were observed at the sodium doublet (5889.953 Å & 5895.923 Å) from May to September, 1997, and in February 1998, using the David Dunlap Observatory (DDO) 1.88m telescope + Cassegrain spectrograph. The setup used provided a dispersion of 0.200 Å/pixel, a spectral range of \(\sim 200 \text{ Å}\), with a resolution of 0.43 Å. This resolution, equivalent to 22 km s\(^{-1}\) at the wavelength of the sodium doublet, is sufficient to detect the sharp lines attributable to individual HI clouds (Wakker & van Woerden 1997).

The target stars were selected primarily from the
Tycho catalog (Hog et al. 1997), the deepest available general catalog of stars with accurate $B-V$ colors. We selected stars which are blue ($B-V < 0.4$), and relatively faint ($V > 9.0$). Such stars are likely to be distant early-type stars, which provide relatively clean continuum emission in the spectral region of interest, and are thus useful as probes for interstellar absorption. The bulk of the observing time was allocated to stars which clearly lay along the line of sight to the Draco Cloud as defined by its IRAS dust emission at 100$\mu$m (Figure 1). This dust should trace the highest column density regions of the cloud (Burton 1996). We expect such stars to show a relatively strong sodium absorption feature (if behind the cloud), easily detected as unresolved lines in moderate strength sodium absorption feature (if behind the cloud). To quantify the nature of the other strong sodium absorption features apparent in the spectra, we have cross-correlated the remaining wavelength portions of the spectra with an appropriate spectral standard (HD173667). The cross-correlations show maxima which have velocities and widths consistent with all other significant sodium absorption features, indicating that these features are likely stellar in origin. The LSR velocities of these stellar features are listed in Table 2. Furthermore, we have used the observed interstellar absorption in TYC 4194 2188 (equivalent width $\approx 0.25$ Å) to compute the expected interstellar absorption in the other three stars, presuming that these stars are also behind the Draco Cloud. This putative absorption has been scaled by the relative total HI column density (due to the Draco Cloud) at each star compared to that at TYC 4194 2188, derived from the Leiden/Dwingeloo HI survey (Hartmann & Burton 1997). The expected absorption is shown in Figure 2. Since their observed spectra do not show the expected absorption, we claim that the other three stars are in front of the Draco Cloud. Note that this assumes that the NaI/HI ratio remains constant across the cloud, and that changes in the HI column density at angular scales less than $\sim 0.5$ degrees do not significantly affect our conclusions.

3. FOREGROUND AND BACKGROUND STARS

The spectra for the four most distant stars are shown in Figure 2. One of these stars (TYC 4194 2188) clearly shows an unresolved absorption feature at the Draco Cloud’s systemic velocity ($V_{LSR}=-23.9$ km s$^{-1}$ ; Heiles, Reach & Koo 1988), and is thus behind the cloud. To quantify the nature of the other strong sodium absorption features apparent in the spectra, we have cross-correlated the remaining wavelength portions of the spectra with an appropriate spectral standard (HD173667). The cross-correlations show maxima which have velocities and widths consistent with all other significant sodium absorption features, indicating that these features are likely stellar in origin. The LSR velocities of these stellar features are listed in Table 2. Furthermore, we have used the observed interstellar absorption in TYC 4194 2188 (equivalent width $\approx 0.25$ Å) to compute the expected interstellar absorption in the other three stars, presuming that these stars are also behind the Draco Cloud. This putative absorption has been scaled by the relative total HI column density (due to the Draco Cloud) at each star compared to that at TYC 4194 2188, derived from the Leiden/Dwingeloo HI survey (Hartmann & Burton 1997). The expected absorption is shown in Figure 2. Since their observed spectra do not show the expected absorption, we claim that the other three stars are in front of the Draco Cloud. Note that this assumes that the NaI/HI ratio remains constant across the cloud, and that changes in the HI column density at angular scales less than $\sim 0.5$ degrees do not significantly affect our conclusions.

4. DISTANCE DETERMINATIONS

To determine the distance to this subset of four stars, high S/N ‘classification’ spectra were acquired, again using the DDO 1.88m telescope + Cassegrain spectrograph. The spectra cover roughly 3750-4350 Å. A suite of standards (from García 1989) were also observed, ranging in spectral type from B0 to G5, and spanning luminosity classes I-V.

The four 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 (see Table 2).

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We have considered three independent 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). The dominant uncertainty is the intrinsic scatter in the $M_V$-MK relation. We have not accounted for extinction, as the expected overall extinction along typical lines of sight at these galactic latitudes is small. Additionally, the extinction on the background star due to the Draco Cloud is uncertain, but likely quite small (Stark et al. 1997). Note that the inclusion of extinction can only reduce the estimated distance of the background star, and hence tighten the distance bracket.

**Individual Stars**

**TYC 4194 2188:** This star, the only one of our sample with detected interstellar sodium absorption due to the Draco Cloud, is also obviously of the earliest spectral type. The best spectral class estimate is A6V, which places it at a distance of ~620 pc.

**BD+64 1134:** This star is an F5 main-sequence dwarf. Though it is quite distant (~380 pc), the weak expected sodium absorption (Figure 2) makes it a poor lower limit, despite the relatively high S/N of the sodium spectrum.

**TYC 4190 1263:** This star is a spectroscopic binary as it shows double stellar lines in the sodium spectral region. The flux ratio of the components is ~2-3, and the best composite spectral classification is an F5/G0 main-sequence dwarf pair. In determining the distance to this star, we have allowed a spectral misclassification of ±1 class for the primary component and ±2 classes for the secondary. This star provides the best lower limit on the Draco Cloud as it is relatively distant (~460 pc), and would be expected to readily show sodium absorption if it were behind the cloud (see Figure 2).

**TYC 4193 691:** This star is about G0, and likely a main-sequence dwarf. The angular separation between it and the background star is quite small, but it is too nearby (~250 pc) to provide a useful lower distance limit.

The derived distances are summarized in Table 2. The background star (TYC 4194 2188) and the most distant foreground star (TYC 4190 1263) set constraints on the distance to the Draco Cloud. This bracket is $463_{-136}^{+192}$ to $618_{-174}^{+243}$ pc, which corresponds to a vertical distance above the galactic plane of $290_{-85}^{+120}$ to $387_{-109}^{+152}$ pc. This is in excellent overall agreement with the much broader distance limits set by other methods (see §1).

5. CONCLUSIONS

We have observed a total of 8 stars in the line of sight towards the Draco Cloud and detected the cloud in absorption at the sodium doublet toward one star. Detailed spectral classifications of this star and the three most distant foreground stars provide a distance bracket of $463_{-136}^{+192}$ to $618_{-174}^{+243}$ pc. This distance is consistent with, but much more precise than, other previous measures by different means. Furthermore, this distance indicates that the Draco Cloud is located outside the Local Hot Bubble and therefore must be shadowing X-ray emission from beyond the LHB.

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REFERENCES

Benjamin, R. A., Venn, K. A., Hiltgen, D. D., & Sneden, C. 1996, ApJ, 464, 836
Blitz, L., Spergel, D. N., Teuben, P. J., Hartmann, D., & Burton, W. B. 1998, preprint [astro-ph/9803251]
Burrows, D. N. & Mendenhall, J. A. 1991, Nat, 351, 629
Burton, W. B. 1996, in The Physics of Galactic Halos, eds. H. Lesch, R.-J. Dettmar, U. Mebold, and R. Schlickeiser, (Berlin: Akademie Verlag), p. 15
Corbally, C. J., & Garrison, R. F. 1984, in The MK Process and Stellar Classification, ed. R. F. Garrison, (Toronto: David Dunlap Observatory), p. 277
Garcia, B. 1989, BICDS, 36, 27
Goerigk, W., & Mebold, U. 1986, A&A, 162, 279
Hartmann, D., & Burton, W. B. 1997, Atlas of Galactic Neutral Hydrogen, (Cambridge: Cambridge Univ. Press)
Heiles, C., Reach, W. T., & Koo, B. 1988, ApJ, 332, 313
Hog, E., Baessgen G., Bastian, U., Egret, D., Fabricius, C., Grossman, V., Halbwachs, J. L., Makarov, V. V., Perryman, M. A. C, Schwekendiek, P., Wagner, K., & Wicenec, A. 1997, A&A, 323, 57
Jaschek, C., & Gómez, A. E. 1998, A&A, 330, 619
Lilienthal, D., Wennmacher, A., Herbstmeier, U., & Mebold, U. 1991, A&A, 250, 150
Marshall, F. J., & Clark, G. W. 1984, ApJ, 287, 633
Mebold, U., Cernicharo, J., Velden, L., Reif, K., Crezelius, C., & Goerigk, W. 1985, A&A, 151, 427
Rohlfs, R. 1986, Diploma Thesis, University of Bonn
Saunders, W. T., Kraushaar, W. L., Nousek, J. A., & Fried, P. M. 1977, ApJ, 217, L87
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
Wennmacher, A. 1988, Diploma Thesis, University of Bonn
Wheelock, S. et al. 1994, IRAS Sky Survey Atlas Explanatory Supplement, JPL Publication 94-11, (Pasadena: JPL)
Fig. 2.— Moderately high resolution spectra (in arbitrary linear intensity units), corrected to the LSR frame, for the four most distant program stars (thick lines) showing both stellar and interstellar sodium absorption features. Note the prominent absorption feature in the spectrum of TYC 4194 2188, at the velocity of the Draco Cloud (dashed vertical lines). The thin dotted lines show the expected effect of similar absorption on the other three stars, as described in §3.
Table 1

**Stars Observed at the Sodium Doublet**

| Star            | V   | B-V  | Int. (ksec) |
|-----------------|-----|------|-------------|
| BD+60 1704\(^D\) | 9.38| 0.372| 3.6         |
| BD+59 1757\(^W\) | 9.45| 0.259| 2.4         |
| BD+60 1703      | 9.55| 0.380| 4.9         |
| TYC 4190 2042   | 11.03| 0.383| 2.4         |
| TYC 4194 2188   | 11.15| 0.121| 5.4         |
| BD+64 1134      | 11.37| 0.044| 20.7        |
| TYC 4190 691    | 11.40| 0.182| 3.6         |
| TYC 4190 1263\(^D\) | 11.41| 0.181| 5.4         |

Note.—Stars noted as 'D' appear as double-lined spectroscopic binaries in the sodium-region spectra, and stars noted as 'W' show strong broadening, consistent with a spectroscopic binary, but with no indication of duplicity in the spectrum. Photometry data are from the Tycho catalog (Hog et al. 1997).

Table 2

**Spectrum Analysis Results**

| Star            | Sp. Class | Dist. | EEW | \(v_{obs}\) |
|-----------------|-----------|-------|-----|-------------|
| TYC 4193 691    | G0V       | 252\(^{+104}_{-74}\) | 0.23 | +4          |
| BD+64 1134      | F5V       | 382\(^{+155}_{-110}\) | 0.05 | -12         |
| TYC 4190 1263   | F5/G0V    | 463\(^{+192}_{-136}\) | 0.20 | +3 +85     |
| TYC 4194 2188   | A6V       | 618\(^{+243}_{-174}\) | —    | -120        |

Note.—Expected equivalent widths (EEW), in Ångstroms, of sodium absorption are given relative to the detected absorption in TYC 4194 2188, as detailed in §3. Also listed are the approximate velocities (in \(\text{km s}^{-1}\)) of the stellar absorption features in these spectra.