Detecting Dark Matter in High-Velocity Clouds

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ABSTRACT. Many high-velocity H I clouds (HVCs) are now believed to be scattered throughout the Galactic halo on scales of tens of kiloparsecs. Some of these clouds appear to contain substantial H I masses (>10^6 M⊙). It has been suggested that these structures may be associated with dark matter “minihalos” accreting onto the Galactic halo. For a compact HVC along the sight line to a more distant galaxy, we demonstrate that “pixel gravitational lensing” provides a crucial test for the presence of a dark halo in the form of massive compact objects. The detection of pixel lensing will provide an independent means of mapping the mass distribution within HVCs.

1. INTRODUCTION

Observations of the Galactic halo make a compelling case that the formation of halos continues to the present day (Wyse 1999). The halo appears to have built up through a process of accretion and merging of low-mass structures which is still going on at a low level. Hierarchical cold dark matter (CDM) simulations, however, predict that the Galactic halo should have many more satellites than are actually observed (Klypin et al. 1999; Moore et al. 1999). Observations reveal that many of the sky is peppered with high-velocity H I clouds (HVCs) which do not conform to orderly Galactic rotation. These are interesting accretion candidates—particularly if they are associated with dark matter “minihalos”—except that their distances, d, are unknown for all but a few sources. As a result, fundamental physical quantities—size (∝ d) and mass (∝ d^2)—are unconstrained, which has encouraged wide speculation as to the nature of HVCs (Wakker & van Woerden 1997; Wakker, van Woerden, & Gibson 1999).

The current renaissance in HVC studies can be traced in part to one paper. Blitz et al. (1999) have shown that the velocity centroids and groupings of positive/negative-velocity clouds on the sky may be understood within a reference frame centered on the Local Group barycenter. They interpret HVCs as gas clouds accreting onto the Local Group over a megaparsec sphere. Braun & Burton (2000) have identified specific examples of compact clouds that have “rotation curves” consistent with CDM mass profiles. For sources at 700 kpc, the kinematic signatures imply a high dark-to-visible mass ratio of 10–50. However, Zwaan & Briggs (2000) note from the Arecibo H I Strip Survey that, of 300 galaxies and 14 galaxy groups, none appear to have properties resembling HVCs associated with the Milky Way or the Local Group. A possible interpretation is that the clouds are somewhat closer to the galaxy or group barycenters.

Reliable distance indicators for HVCs are presently hard to come by. Oort (1966) proposed virial distances on the assumption that HVCs are self-gravitating. The mass inferred from the H I column density has a different distance dependence than the gravitationally inferred mass from the H I line width. This crude method puts some HVCs at megaparsec distances (Blitz et al. 1999; Braun & Burton 1999). An alternative method is to use bright sources with well-calibrated distances along the sight line to gas clouds. If the cloud produces absorption in the spectrum of one source but not in the other, the cloud distance can be bracketed. This method establishes that two HVCs are within 10 kpc of the Sun (van Woerden et al. 1999).

We have recently developed the Hα distance method, which has the potential to reach much greater distances (Bland-Hawthorn et al. 1998; Bland-Hawthorn & Maloney 1999a, 1999b). If a gas cloud is optically thick to ionizing radiation from a source with known luminosity, the Hα flux can be used to infer the external field strength and therefore the cloud’s distance from the source. Two groups have now used this method to show that many HVCs are faint or invisible in Hα and appear to be distributed on scales of tens of kiloparsecs throughout the Galactic halo. Some of these clouds have H I masses in excess of 10^6 M⊙ (B. J. Weiner et
of the universe, by a "concentration" such as the halo within which the average is 200 times the critical density. A scale radius which is related to (the radius of the halo within which the average is 200 times the critical density of the universe, $\rho_{\text{crit}}$), by a "concentration" $c_s$, such that $r_{200} = c_s r_s$. The (dimensionless) characteristic density, $\delta_s$, is simply related to $c_s$ by

$$\delta_s = \left( \frac{200}{3} \right) \frac{c_s^3}{\log (1 + c_s) - c_s(1 + c_s)}.$$ (2)

We adopt this profile in describing the dark matter distribution in HVCs. For a particular halo mass, defined as $M_{200} = M(<r_{200})$, the concentration $c_s$ depends on the halo collapse redshift, and hence the cosmology, power spectrum, etc. Assuming $\Omega_0 = 1$ and $\Lambda_0 = 0$, we employ the recipe provided by NFW to determine the halo profiles in a standard CDM cosmology. A numerical routine for calculating these profiles was kindly provided by J. Navarro.

Bartelmann (1996) and Wright & Brainerd (2000) have considered the gravitational lensing properties of massive galaxy clusters with NFW mass profiles. Rather than the radial density distribution (eq. [1]), the important quantity in such an analysis is the projected surface mass density. This is given by

$$\kappa(x) = 2\kappa_s \frac{f(x)}{x^2 - 1},$$ (3)

where $x = r/r_s$. The normalizing factor is given by $\kappa_s = \frac{\delta_s r_s \rho_{\text{crit}}}{\Sigma_{\text{crit}}}$, where $\Sigma_{\text{crit}}$ is the critical surface mass density to gravitational lensing,

$$\Sigma_{\text{crit}} = \frac{c_s^2}{4\pi G} \frac{D_{\odot}}{D_{\odot} D_{\text{ls}}},$$ (4)

where $D_{ij}$ are the angular diameter distances between the observer ($o$), lens ($l$) and source ($s$). The auxiliary function $f(x)$ is given by

$$f(x) = \begin{cases} 1 - \frac{2}{\sqrt{1-x^2}} \frac{\arctanh \left( \frac{1-x}{\sqrt{1+x}} \right)}{(x < 1),} \\ 0 \quad (x = 1), \\ 1 - \frac{2}{\sqrt{x^2 - 1}} \frac{\arctan \left( \frac{x-1}{\sqrt{x+1}} \right)}{(x > 1)}. \end{cases}$$ (5)

Defining $g(x) = f(x)/(x^2 - 1)$, the normalized surface mass density is given by

$$\kappa(x) = 3.33 \times 10^{-13} \frac{\delta_s}{c_s} r_{200} D_{\odot} \left( 1 - \frac{D_{\odot}}{D_{\text{ls}}} \right) g(x) h^2,$$ (6)

where all distances are in kiloparsecs and it is assumed that only objects in the local universe are considered, such that $D_{\text{ls}} = D_{\odot} - D_{\text{ls}}$. The Hubble parameter, $h$, is defined such that $H_0 = 100 h$ km s$^{-1}$ Mpc$^{-1}$.

2.2. Lensing Properties

Armed with these various tools, we can now examine the gravitational lensing properties of dark matter halos of HVCs. Considering fiducial masses of $M_{200} = 10^6, 10^7, 10^8$, and $10^9 M_\odot$, corresponding to the potential dark matter masses of HVCs, we determined the NFW parameters; these are summarized in Table 1. First, it is important to determine whether the projected surface density of these dark matter halos is sufficient to induce macrolensing effects, resulting in multiple images; in the absence of strong shearing, this requires the normalized surface mass density, $\kappa$, to exceed unity. An examination of equations (3) and (5) reveals that $\kappa(x)$ becomes singular at $x = 0$ and must meet the criterion for producing multiple images at some radius.

### Table 1

<table>
<thead>
<tr>
<th>$M_{200}$ ($M_\odot$)</th>
<th>$\delta_s$</th>
<th>$c_s$</th>
<th>$r_{200}$</th>
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<td>$10^6$</td>
<td>1.66 $\times 10^6$</td>
<td>40.95</td>
<td>1.63</td>
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<tr>
<td>$10^7$</td>
<td>1.21 $\times 10^7$</td>
<td>36.40</td>
<td>3.51</td>
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<td>$10^8$</td>
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<td>31.95</td>
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<td>$10^9$</td>
<td>5.87 $\times 10^9$</td>
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Note.—While $\delta_s$ and $c_s$ are dimensionless, $r_{200}$ is in kpc. These values were calculated assuming $h = 1$. 2000 PASP, 112: 1300–1304
At small $x$, the surface density becomes

$$\kappa(x) \sim 2\kappa_s \log \left( \frac{2 - 1}{e} \right).$$

(7)

Considering the parameters in Table 1, and placing the HVC at any reasonable distance, $\kappa(x)$ does not exceed unity until very small (and unphysical) radii. Therefore, such halos are unable to produce observable macrolensing effects and the dark matter cannot be probed by looking for “image splitting” of distant sources. However, if the dark matter in HVC is in the form of compact objects, these will introduce microlensing variability into the observations of background sources. As potential sources are extragalactic, namely, galaxies, the resulting microlensing is unlike that in the Magellanic Clouds and the Galactic bulge, where an individual star is seen to brighten and fade as a compact object crosses the line of sight. Rather, as a patch of light from a distant galaxy represents an unresolved population of stars, any microlensing will be seen as against this smooth background. Hence, microlensing will be detected as fluctuations in surface brightness over the source galaxy. The framework of this “pixel lensing” was laid down by Crotts (1992) and Gould (1996), and has recently proved successful in a search for compact objects along the lines of sight to M31 and the Galactic bulge (Crotts & Tomaney 1996; Tomaney & Crotts 1996; Alcock et al. 1999). Pixel lensing has also been proposed as a tool to search for both intracluster compact objects (Gould 1995; Lewis, Ibata, & Wyithe 2000) and cosmologically distributed dark matter (Lewis & Ibata 2000).

Using equation (6), and considering the NFW parameters presented in Table 1, the microlensing optical depths for the dark matter halos can be calculated. By assuming that the halo lies at a distance of 100 kpc from the Earth, in front of a source at 3 Mpc, Table 2 presents the optical depths at several angular radii. It is immediately apparent that the optical depths for all the models are small, in the regime probed by the microlensing searches toward the Galactic bulge and halo. Given the subcritical value of the microlensing optical depth seen through the dark matter halos associated with the HVCs, the expected number of “pixel-lensing” events simply scales as $\Gamma \propto \kappa$ (see Binney 2000). Hence, in searching for HVC compact dark matter objects, a simple test presents itself; in monitoring the surface brightness distributions of galaxies, regions that overlap with the dark matter halos of HVCs will display pixel-lensing variability. Moreover, as the optical depth increases toward the center of the HVC systems, the resultant number of microlensing events should also increase toward the center. Given the simple linear scaling between the number of events and the surface mass density, the identification of microlensing of systems viewed through HVCs will not only detect the dark matter component but will also provide a (nonkinematic) map of the dark matter mass over tens to hundreds of arcseconds, depending upon the mass of the halo. A detailed calculation of the optical depth distribution for specific HVCs and source galaxies is beyond the scope of this current paper and will be presented elsewhere. A simple estimate of the expected number of events can be found by extrapolating the analysis of Binney (2000), who determines that for an optical depth of $\kappa = 10^{-6}$ and sources at 50 Mpc, monitoring with a 4 m class (diffraction-limited) telescope will uncover three or four events per $10^6$ resolution elements per week. For a similar source distance, and an HVC located at 100 kpc, the optical depths in the central regions of the halos presented in this paper are greater than $10^{-6}$, with $10^9 M_\odot$ exceeding this by a factor of $\sim 50$ over a region 10° in radius. Increasing the distance to the HVC will similarly increase the number of expected microlensing events. This analysis indicates that if HVCs are enshrouded in halos of compact dark matter, then a substantial number of microlensing events should be detectable.

One potential contaminant is microlensing of the sources by compact objects within our own Galactic halo or that of the potential source. Binney (2000) recently examined the sky distribution of halo microlensing optical depth to distant sources within several models for the mass distribution of the Galaxy. The optical depth is greatest in the disk of the Galaxy, and falls rapidly with Galactic latitude, falling below $10^{-6}$ for $|b| \geq 12^\circ$. At these higher Galactic latitudes even the least massive halo considered in this paper will dominate the microlensing optical depth along a line of sight by a factor of 10. Similarly, the optical depth through the halo of the source will also be of order $10^{-6}$ and show a similar distribution over the galaxy. Microlensing by material in the HVC halo will enhance this value, and will be spatially correlated with the HVC core, making it distinguishable from any intrinsic “self-lensing.”

Recent results from the MACHO (Alcock et al. 2000a) and EROS (Lasserre et al. 2000) studies toward the Magellanic Clouds suggest that only $\sim 20\%$ (at most) of the dark

<table>
<thead>
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<th>$M_{200}$ ($M_\odot$)</th>
<th>1°</th>
<th>10°</th>
<th>100°</th>
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</thead>
<tbody>
<tr>
<td>$10^2$</td>
<td>$8.5 \times 10^{-6}$</td>
<td>$3.8 \times 10^{-6}$</td>
<td>$5.4 \times 10^{-7}$</td>
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<td>$10^1$</td>
<td>$1.8 \times 10^{-5}$</td>
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<tr>
<td>$10^0$</td>
<td>$3.8 \times 10^{-5}$</td>
<td>$2.3 \times 10^{-5}$</td>
<td>$8.8 \times 10^{-6}$</td>
</tr>
<tr>
<td>$10^{-1}$</td>
<td>$7.4 \times 10^{-5}$</td>
<td>$4.9 \times 10^{-5}$</td>
<td>$2.4 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Note.—The halo is placed at a distance of 100 kpc, in front of a source at 3 Mpc. At this distance, 100° corresponds to 48.5 pc. The optical depths can be scaled to other distances using eq. (6).
matter halo of the Galaxy resides in the form of compact objects. If this is the case, and the distribution of dark matter is universal, then the optical depths presented for the HVCs would have to be scaled by a similar factor. However, if the dark matter in the Galactic halo is clumped on large scales, then our view to the Magellanic Clouds may be through a relatively empty region. Such a picture, which is consistent with the hierarchical accretion model discussed in this paper (see Klypin et al. 1999), may explain why our view toward the Galactic bulge appears to be relatively overdense in MACHOs (Binney, Bissantz, & Gerhard 2000; Alcock et al. 2000).

3. PROPOSED EXPERIMENT

The practical limitations to the pixel lensing technique described in § 2 are, of course, set primarily by the availability, or lack thereof, of (purported) dark matter–dominated HVCs suitably aligned with background galaxies. To a 5σ limiting H I column density of \(7 \times 10^{17} \text{cm}^{-2}\), Murphy, Lockman, & Savage (1995) claim an HVC sky covering fraction of \(\sim 37\%\). The high detection rate of high-velocity Galactic Mg II gas seen toward background quasars (Savage et al. 1993) implies a covering fraction of \(\sim 50\%\) at column densities of \(2 \times 10^{17} \text{cm}^{-2}\). Clearly, high-velocity gas does exist, at some level, along virtually all extragalactic sight lines. Unfortunately, one needs to exercise restraint before proclaiming that the pixel-lensing experiment will therefore be a trivial one.

Of greatest concern is the potential contamination due to the inclusion of “non–dark matter–dominated HVCs” in the above sky covering fractions. Eliminating large, diffuse HVCs from the above sample (e.g., Magellanic Stream, complexes A, C, and M), and restricting the analysis to unresolved (<1 deg²), isolated HVCs, immediately reduces the covering fraction by a factor of \(\sim 50\%\) to \(\sim 0.7\%\) (Blitz & Robishaw 2000). An even more stringent sampling was adopted by Braun & Burton (1999) in constructing their Compact High-Velocity Cloud (CHVC) catalog, resulting in a compilation of only 65 candidates. Subsequent high-resolution imaging of a subset of these CHVCs (Braun & Burton 2000) shows that each is \(\sim 0.2\) deg² in areal extent, for a total sky covering fraction of \(\sim 0.03\%\), more than 3 orders of magnitude lower than that found by Murphy et al. (1995). The southern sample of CHVCs in the Braun & Burton catalog was necessarily limited to the older H I survey by Bajaja et al. (1985); this has since been supplanted by the Morras et al. (2000) survey (a direct southern analog to the Leiden-Dwingeloo Survey [Hartmann & Burton 1997] and the H I Parkes All-Sky Survey [HIPASS; Putman & Gibson 1999a, 1999b]). The latter survey is particularly attuned to the discovery of CHVCs, as it is the first of its kind to sub-Nyquist–sample the southern sky. A visual inspection of several random HIPASS data cubes demonstrates that a factor of 2 increase in the number of known southern CHVCs (with H I column densities greater than \(10^{18} \text{cm}^{-2}\)) can be expected.

As Blitz & Robishaw (2000) demonstrate, the probability of a chance alignment of a CHVC with a nearby, background galaxy is \(\sim 1\%\). Even allowing for the aforementioned expected increase in the number of cataloged CHVCs, this probability will remain less than \(2\%\). On the other hand, if the simulations of Klypin et al. (1999) and Moore et al. (1999) are correct, one might expect there to be 300–500 CHVCs in the Local Group, of which only \(\sim 100\) have been accounted for. Perhaps deeper H I surveys will uncover this missing population, or perhaps they will only be discovered serendipitously through studies of background quasars. Regardless, the inclusion of this additional hidden population of CHVCs would increase the probability of finding a CHVC background galaxy alignment to \(3\%–5\%\).

Obviously, this will be a challenging experiment, but not an impossible one. We are initiating a search through the HIPASS data cubes, in an attempt to uncover prospective candidates. Several possibilities currently exist, although we stress that this is neither a finalized nor a complete list: HIPASS 1328 – 30 (Banks et al. 1999) and ESO 383-G087, both in the Cen A group, NGC 3109 in the Antlia-Sextans grouping, and NGC 55 and AM 0106 – 382 in Sculptor each have CHVCs lying in the range 15°–30°, yet kinematically separated, from the galaxy.

4. CONCLUSIONS

Cold dark matter models for the formation of universal structure predict that the Galaxy should be surrounded by many infalling “clumps” of material. While the Galaxy is accompanied by a number of dwarf galaxies, they cannot account for the total expected population of objects. Recently it has been suggested that high-velocity clouds are accompanied by halos of dark matter and hence represent, and trace, the missing dark matter population.

In this paper we have demonstrated that while HVCs are too diffuse to produce macrolensing splitting of distant sources, if their dark matter consists of compact objects, then this adds to the microlensing optical depth. This signal is detectable with a 4 m class telescope and a modest observing campaign over a year, and provides a map of the underlying dark matter distribution. While chance alignments of HVCs with more distant galaxies are not common, several potential sources already present themselves. This situation is likely to improve as current data are scanned and future observations are undertaken. We eagerly await the monitoring of a “minihalo” candidate HVC along the sight line to a nearby galaxy.
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