THE ABSENCE OF STARS IN COMPACT HIGH-VELOCITY CLOUDS

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ABSTRACT

We present the results of our search for faint Local Group dwarf galaxies in compact high-velocity clouds (HVCs). We used digitized Palomar Observatory Sky Survey (POSS) data to examine 1 deg$^2$ of sky around each of ~250 northern hemisphere HVCs. The POSS images were processed to remove foreground stars and large-scale backgrounds, smoothed to enhance arcminute-sized low surface brightness features, and then compared with the original plates. Using this technique, we located 60 candidate dwarf galaxies in the ~250 deg$^2$ that we surveyed. Follow-up observations of these candidates have revealed several distant clusters of galaxies and a number of possible Galactic cirrus clouds, but no Local Group dwarfs. It appears that many of the low surface brightness features in the sky survey data are plate flaws. The second-generation red POSS plates are sensitive down to surface brightness levels of 25–26 mag arcsec$^{-2}$, and our follow-up images reached 10 $\sigma$ limiting magnitudes of $R = 21–23$ for point sources. Given these limits, all known Local Group galaxies except four of the very diffuse, extended dwarf spheroidals located within 100 kpc of the Milky Way would have been detected had they been in our survey. Therefore, we can rule out the possibility that these HVCs are associated with normal but faint dwarf galaxies. If compact HVCs do contain stars, they must have surface brightnesses $\gtrsim 1$ mag arcsec$^{-2}$ fainter than most known Local Group galaxies.

Subject headings: galaxies: dwarf — intergalactic medium — Local Group

1. INTRODUCTION

The nature of the high-velocity clouds (HVCs) of neutral hydrogen has been a source of controversy since their discovery almost 40 years ago and remains so today. It now appears that HVCs do not represent a single phenomenon. Rather, they are an amalgam of several types of objects that were grouped together by the extremely broad observational definition of “HVC”: neutral hydrogen that is moving at velocities inconsistent with simple models of Galactic rotation. Some HVCs, notably the Magellanic Stream, are composed of gas that has been either tidally or ram-pressure stripped out of the Magellanic Clouds. Others are very extended clouds close to the Milky Way (distances of a few to a few tens of kiloparsecs), whose origin is not clear, although they appear to be extragalactic. Finally, there is a large population of small clouds (in angular size) whose properties have proven very difficult to determine. These were labeled compact HVCs by Braun & Burton (1999, hereafter BB99) and may represent a relatively homogeneous class of objects. We concentrate on these HVCs for the remainder of this paper.

One hypothesis that has received attention is that HVCs are clouds of primordial gas in the Local Group and thus are located at typical distances from the Milky Way of up to 1 Mpc (Oort 1966, 1970; Verschuur 1969; Kerr & Sullivan 1969). Blitz et al. (1999, hereafter B99) have recently proposed a dynamical model based on this idea that simulates the evolution of the Local Group. The model is able to explain the properties of HVCs as the postulated primordial clouds, left over from the formation of the Local Group and currently falling into the Local Group barycenter. In addition to reproducing observed results of the spatial distribution and kinematics of HVCs, B99 make observational predictions about HVC internal pressures, metallicities, and H$\alpha$ emission, all of which are being actively investigated.

Other potentially viable theories to explain the HVC puzzle include the Galactic fountain model (Shapiro & Field 1976; Bregman 1980) and the tidal debris model. According to the Galactic fountain model, large numbers of supernova explosions in the inner Galaxy expel hot, metal-rich gas from the Milky Way’s disk into the halo. These clouds then cool and fall back toward the Galaxy and are seen as HVCs. In contrast, the tidal debris model proposes that all HVCs are remnants of the tidal interaction between the Milky Way and the Magellanic Clouds.

The best way to settle the question of the origin of HVCs is to measure their distances, since the three models prefer distances that differ by 2 orders of magnitude. In this paper, we describe our search for stars in HVCs, which if present could be used for photometric distance estimates. Despite the large amount of observational effort at 21 cm that has been devoted to HVCs, there have not yet been any systematic, large-scale searches for stars.

In § 2 we discuss the motivations for this work in more detail. Readers who are already familiar with the recent HVC literature may wish to skip ahead. We describe our search technique and discuss the data sets used in our analysis in § 3. We briefly present the results of our search of the Palomar Observatory Sky Survey (POSS) data in § 4. In § 5 we describe our follow-up observations. The limits we have placed on the stellar content of HVCs and the implications of our results are discussed in § 6, and our conclusions are presented in § 7.

2. MOTIVATIONS

2.1. Recent HVC Results

Recent observations of HVCs have tended to at least roughly agree with the predictions made by B99. The internal pressures of high-velocity clouds, as determined by
ultraviolet absorption-line studies, are low in the few clouds that have been observed. This finding is consistent with the HVCs being Local Group objects (Sembach et al. 1999). The metallicities of HVCs (other than the Magellanic Stream material) have been found to be 0.1–0.3 times solar, also within the range predicted by B99 (Wakker et al. 1999; Murphy et al. 2000; Richter et al. 2001; Gibson et al. 2001). Some of these measurements are toward the high end of what can be reasonably accommodated by the Blitz et al. model, and if lower metallicity HVCs are not found, this may eventually present a problem for the extragalactic hypothesis. The Galactic fountain model, however, faces an even bigger challenge, since it predicts solar or higher metallicities for high-velocity gas. It should be noted that all these metallicity determinations are for nearby HVCs that are part of the large complexes. These complexes are believed to be interacting with the Milky Way and might have been partially enriched as a result. Therefore, these metallicity measurements do not necessarily apply to the presumably more distant and isolated compact clouds, and in fact can be regarded as upper limits to the metallicities of compact HVCs. A further caveat to the metallicity determinations is that they rely on comparing optical and UV absorption column densities, which probe gas on scales of $\sim 10^{-4}$ arcsec, with H$\alpha$ observations on an angular scale at least 4 orders of magnitude larger. The effects of this mismatch are not known.

H$\alpha$ emission from HVCs has also been observed, but the results of this work are difficult to interpret. A number of researchers have used Fabry-Perot instruments to detect $\sim 20$ HVCs in H$\alpha$, and sometimes also in the nearby N $\pi$ and S $\pi$ emission lines (Kutyrev & Reynolds 1989; Tuft, Reynolds, & Hoffner 1998; Bland-Hawthorn & Maloney 2002; Weiner, Vogel, & Williams 2002). By comparing the strength of the emission from these clouds with that from gas at known distances (e.g., nearby complexes or the Magellanic Stream), one can estimate the distances to the HVCs. Bland-Hawthorn & Maloney (2002) and Weiner et al. (2002) conclude based on their observations that the HVCs they detect are probably nearby, at distances of tens of kiloparsecs. However, their method depends critically on the assumption that HVC ionization is caused primarily by photoionization from the Milky Way’s UV field. Although this assumption seems reasonable, it appears to be false for the Magellanic Stream gas (Weiner & Williams 1996). Furthermore, these calculations do not work well for one object whose distance is known: the Sculptor dwarf spheroidal galaxy (dSph). Sculptor is located 80 kpc from the Milky Way, yet it is brighter in H$\alpha$ than complexes A, C, and M, which are all an order of magnitude closer. If the HVC distance estimates are normalized to Sculptor instead of to complexes A and M, significantly larger distances (up to $\sim 200$ kpc) are derived. In support of the shorter distance scale, Weiner et al. (2002) note that none of the HVCs they observe have fluxes close to their detection limit; every object is at least an 8 $\sigma$ detection. They argue that the lack of H$\alpha$-faint HVCs implies that HVCs are not very far away. As with the metallicity studies cited above, however, many of these observations have been of the HVC complexes that were already known or suspected to be nearby. Until there has been a comprehensive H$\alpha$ survey of the compact HVCs and there is a reliable way to relate HVC H$\alpha$ fluxes to distances, these observations will not offer strong confirmation or refutation of any HVC models.

2.2. A New Technique

Faced with this confused state of affairs, we decided to take a different approach to the HVC problem. The key objects are the ones whose nature is most uncertain: compact HVCs. Since there does not appear to be a simple way to determine their distances directly with current techniques, we have attempted an indirect method: searching for stellar counterparts to the HVCs. If we could detect such stars, it would be straightforward to obtain accurate photometric distances to them and thereby conclusively establish the nature of the high-velocity clouds.

Several lines of evidence have recently led to the hypothesis that HVCs are likely to contain stars. First, blind H$\i$ surveys of nearby galaxies and groups have found that the low-mass H$\i$ clouds they detect are often associated with low surface brightness (LSB) dwarf galaxies (Banks et al. 1999; Kraan-Korteweg et al. 1999; Pisano & Wilcots 1999; Rosenberg & Schneider 2000; Boyce et al. 2001). This suggests that the Local Group H$\i$ clouds might be similarly associated with currently undiscovered dwarf galaxies. Second, H$\i$ has now been detected toward half of the Local Group dSphs and all of the dwarf irregular galaxies (dIrrs; Blitz & Robishaw 2000). In one case, this H$\i$ may have been previously classified as an HVC (HVC 561 and Sculptor have very similar positions and velocities) by Wakker & van Woerden (1991). The H$\i$ around the dSphs appears to be very extended compared to the optical galaxies and is of similar physical size and mass to the HVCs as described by B99. These similarities support the idea that HVCs and H$\i$ in dSphs could be related objects.

A further reason to suspect that HVCs might be associated with dwarf galaxies comes from numerical simulations of cold dark matter (CDM) cosmological models. It has become well known that these simulations produce too much substructure (Klypin et al. 1999; Moore et al. 1999). In simulated Local Groups, the mass concentrations around Milky Way and M31 analogs contain up to a few hundred small dark matter halos. The real Local Group is comparatively barren, with only $\sim 35$ known dwarf galaxies. If CDM is correct and these dark matter minihalos exist, they probably would have accreted some gas, and then could subsequently have formed stars (although, see Bullock, Kravtsov, & Weinberg [2000] for one explanation of why star formation might be suppressed in such objects). In any case, it has been suggested by several authors that compact HVCs could be these "missing" dark matter halos (e.g., Klypin et al. 1999; Moore et al. 1999).

Finally, it is almost certain that the census of Local Group galaxies is not yet complete. In the past few years, four new dSphs have been discovered: And V by Armandroff, Davies, & Jacoby (1998, hereafter A98), and VI by Karachentsev & Karachentseva (1999, hereafter KK99) and Armandroff, Jacoby, & Davies (1999) independently, And VII by KK99, and Cetus by Whiting, Hau, & Irwin (1999). A fifth dSph, Antilia, was first cataloged by Corwin, de Vaucouleurs, & de Vaucouleurs (1985) and Feitzinger & Galinski (1985) and detected in H$\alpha$ by Fouque et al. (1990), who suspected it to be a Local Group member. Follow-up photometry confirming this conjecture was not acquired until the galaxy was rediscovered by Whiting, Irwin, & Hau (1997) several years later. In addition to these recent discoveries, Mateo (1998) notes that there is an apparent deficit of dwarf galaxies at low Galactic latitudes (relative to a uni-
form distribution on the sky). On this basis, he postulates up to 15–20 Local Group dwarfs remaining to be discovered at $b \leq 30^\circ$.

3. SEARCH METHODOLOGY

3.1. POSS Image Processing

The machinery for our search is based loosely on the work of A98 for their similar project (a blind survey for dSph companions of M31). Starting from the outline they provided, we developed an algorithm that processes digitized POSS images\(^1\) from the Space Telescope Science Institute (STScI) to enhance extended LSB objects of the appropriate angular size to be Local Group dwarf galaxies. We adopt similar steps, but in a different order and with significant changes in implementation from A98. The algorithm is described in detail in the following paragraphs. All of the image processing was done in the IDL environment.

We first attempt to remove the brightest stars from the image. Because these stars have such extensive wings, this task is incompletely successful, at best. Nevertheless, we can remove enough of the flux that these stars will not dominate the smoothed image, even though they will still be visible. Bright stars are located with a simple count threshold; any pixel with a value of more than 23,000 counts was defined to be part of a bright source. This method can succeed because our search largely employed the POSS II red plates (for \(\sim 80\%\) of our targets), which tend to have similar sky background levels (5000–6000 counts on average) and sensitivities. Having found the brightest stars, we create a circular mask around each one and replace the pixels in the mask with an average of the surrounding pixels.

This process is repeated in order to remove the fainter stars from the image as well. However, because objects other than faint stars can have peak brightnesses as high or higher than those of the stars, we must use a slightly different technique to detect these stars. We pass a small (\(\sim 10^\circ\)) median filter over the image and then subtract the filtered version from the original. Point sources are seriously degraded in flux in the filtered image and so appear bright in the difference image. Extended sources are only minimally affected by the filtering and are therefore largely removed by subtracting the images. Objects brighter than a threshold value of 1000 counts pixel\(^{-1}\) in the difference image are likely to be foreground stars. The point sources selected with this criterion are masked out and replaced, as described above.

Now that the image is relatively free of stellar light, we must deal with the other major contaminant, the background. Unfortunately, the digitized POSS plates are not flat, especially near the edges, and these background variations significantly hamper a search for LSB galaxies. In order to detect the small increases in surface brightness over a limited area that are associated with dwarf galaxies, the vignetting of the plates and any other large-scale flaws in them must be removed as accurately as possible. We experimented with two-dimensional polynomial fits to the background, but determined that the most reliable means of subtracting just the background (and leaving objects of interest alone) was simply to employ a very wide median filter. The filter must be large enough not to pick up significant signal from dwarf galaxies, or else this procedure could become counterproductive. The largest of the distant dSphs are \(\sim 5^\circ\) across, so a filter more than 10\(^\circ\) wide will be at least 4 times as large as any dwarf galaxies it encounters. Empirically, this level of filtering seemed to be safe, so we chose a filter width of 600 pixels, corresponding to 10\(^\prime\)1 on POSS II and Equatorial Red plates, and 17\(^\prime\) on POSS I and SERC-J plates. To deal with the 300 pixel border around the image where the median filter was too close to the edge to function, we simply replicate the last line or column that the median filter did produce outward to the edges of the image.

After removing the background, we treat the bright stars again, because they still tend to be the brightest sources left in the image (although not overwhelmingly so). At every location where a bright star was removed earlier, we check to see if the average brightness is still more than half a standard deviation above the median for the image. If so, we cut out a larger mask around these remnants, and again replace it with an average of the surrounding pixels.

Finally, we smooth the image with a dwarf galaxy–sized filter in order to further dim the remaining stellar light and thereby enhance the relative contrast between high and low surface brightness objects. We use a Gaussian filter here rather than a median filter because the filter size is such that a median filter runs the risk of smoothing away the entire image. According to Davies et al. (1994), to optimally detect LSB objects, the filter should be roughly the same size as the object. At the distances we expect for the HVCs—300 kpc to 1 Mpc—dwarf galaxies have angular sizes between 1\(^\prime\) and 6\(^\prime\). Therefore, we use a 70 pixel (=71\(^\prime\)0 on POSS II images and 119\(^\prime\) on POSS I images) filter. We choose a filter on the small end of the dwarf galaxy size range because (1) most of the detected objects will be at large distances (due to the greater survey volume there) and (2) we do not want to degrade potential dwarf galaxy signals by smoothing over too large a scale. Since we are not using adaptive filtering here, we are not sensitive to LSB sources of all possible angular sizes. Objects that are smaller than \(\sim 30^\prime\) may be missed by our search because of this final filter, and objects larger than \(\sim 15^\prime\) could be removed by our background filter.

The free parameters in this algorithm (order of steps, mask and filter sizes, etc.) were tuned by extensive testing on known dSphs, primarily the six eponymous companions of Andromeda. In Figure 1, we compare processed images of two of the lowest surface brightness Local Group dSphs with the original POSS II plates. It is clear that the algorithm works well. Even though the dwarfs are barely visible in the unprocessed POSS II images, they are the brightest objects in the field of view—dominating the 10th magnitude foreground stars—after smoothing.

3.2. HVC Catalogs

We used the catalog of compact high-velocity clouds provided by BB99 as the basis for the first part of our search. They selected HVCs visually from the Leiden/Dwingeloo Survey of Galactic Neutral Hydrogen (Hartmann & Burton 1997) and from the large HVC catalog compiled by Wakker & van Woerden (1991). BB99 identified a subset of 65 clouds

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\(^1\) The Digitized Sky Survey was produced at the Space Telescope Science Institute under US government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions.
that are both small (less than 2° in diameter) and isolated from neighboring emission. They claimed that these objects represent a distinct class of HVCs and are all at Local Group distances. We included 59 of these HVCs that were located outside the zone of avoidance (|b| > 5°) in our sample. BB99 also presented ~15 deg² H I maps around each of the compact HVCs (see their Fig. 1). In many of these moment maps, there are nearby clouds that have comparable intensities. Since it is not entirely clear why these clouds were not included in their catalog, we have chosen 17 of the most prominent of them to use in our analysis as well, for a total of 76 HVCs from BB99.

In addition to these compact HVCs, we also selected targets from the new catalog by T. Robishaw & L. Blitz (in preparation, hereafter RB02), a complete sample derived from an automated search of the Leiden/Dwingeloo Survey (LDS). Since this catalog is a work in progress, we were forced to take a fairly simplistic approach to defining HVCs. We first selected all H I detections at velocities less than \( V_{\text{LSR}} = -200 \text{ km s}^{-1} \) or greater than \( V_{\text{LSR}} = 200 \text{ km s}^{-1} \). From this list, we grouped the H I detections into clouds by defining as part of a single object all H I within 3° in both longitude and latitude and within 10 km s\(^{-1}\) in velocity of the brightest point (the brightest point was also defined as the central position). We then culled this list to eliminate HVCs that could not be observed easily from Lick Observatory (clouds outside the range \(-10° \leq \delta \leq 65°\)). This left us with 201 HVCs. It should be noted that while the final RB02 catalog will be a flux-limited sample down to the sensitivity limit of the LDS, this preliminary version is not. We have certainly missed a number of HVCs by focusing only on the highest velocity clouds. Furthermore, these HVCs are not entirely the compact specimens that we believe are the most distant objects; some of the northernmost Magellanic Stream clouds met the criteria described above, and so have been included. Still, many of these clouds are indeed compact HVCs, and the combination of this list with the catalog of BB99 should include most of the compact HVCs in the northern hemisphere. (Putman et al. [2002] found 179 compact HVCs and 159 slightly more extended clouds in the southern hemisphere in their search of the HIPASS data, and there should be a comparable number in the northern hemisphere.) The positions that we searched are plotted on the sky in Figure 2. Finally, we point out that 12 of the BB99 HVCs and one of the secondary clouds are also in the RB02 catalog (the others are excluded by the velocity and declination restrictions). In these cases, we searched around the central positions given by each catalog, so there was necessarily some overlap. Several of the RB02 HVCs are also separated from each other by less than 1°. Taking such occurrences into account, our survey covers 264 unique HVCs and approximately 239 deg² of sky. We also searched 54 deg² in areas that do not contain an HVC, which can be used for a comparison of results.

Fig. 1.—Demonstration of our POSS processing algorithm. On the left are POSS II red images of two of the lowest surface brightness dSphs in the Local Group: And V (top) and Cetus (bottom). The galaxies are just visible as faint smudges at the center of each frame. On the right are the same fields after applying our algorithm. In each case, the dSph has become the brightest object in the image.
3.3. Sky Survey Images

STScI has made available digitizations of the following sky surveys that are of use to us: 2 POSS I3 (red plate only) for the northern hemisphere, POSS II9 (red plate only) for approximately 2/3 of the northern sky, SERC-J4 plates (blue) for the southern sky, the Second Epoch Survey (SES; red) for a small fraction of the southern hemisphere, and the Equatorial Red plates for the region around \( \delta = 0^\circ \). This means that at any position, we only have access to images of one color, except for a small band around the equator. Furthermore, many positions are only covered by a single plate (especially at \( \delta \leq -3^\circ \)) from one of these five surveys, making it difficult to distinguish the numerous plate flaws and background variations from real astronomical objects.

By examining the existing data on \( \text{H}\alpha \) in known dSphs, we determined that in most cases, the centroid of the \( \text{H}\alpha \) distribution is less than 30\arcmin from the optical galaxy. Of the 10 dSphs found by Blitz & Robishaw (2000) to contain \( \text{H}\alpha \) gas, seven meet this criterion and therefore would have been discovered in our survey if they had not already been known. Extending the search radius to 1\arcmin would guarantee that we would find virtually all dSphs that are similar to the known ones, but we judged that the 400\% increase in area to search that this would require was not worth the \( \sim 40\% \) gain in sensitivity. Thus, in our survey for new galaxies, we searched a box 1\arcmin on a side centered on each HVC in the sample. For the BB99 compact HVCs, we used the POSS I and SERC-J survey data, because they had the most complete sky coverage. After completing this, a 30\arcmin wide box around each HVC position was reexamined using POSS II, SES, or Equatorial Red plates, as available. This process gave us greater sensitivity in the area near the center of each HVC. By the time we reached the RB02 HVCs, most of the POSS II data were on-line, so we performed our search of these objects with only the 1\arcmin POSS II images (or the best other plate if no POSS II plate was available).

The search was carried out by processing our downloaded images with the algorithm described above. We compared the processed frames with the originals, blinking back and forth between them. LSB objects showed up as bright spots on the processed images. Every position where such a bright spot was seen and no obvious stellar or galactic counterpart was visible on the unprocessed image was flagged. After this comparison, each flagged region was examined closely by eye on the unprocessed image, using various stretches to best view the LSB feature. Some of these smudges were clearly related to bright Galactic cirrus, other types of nebulae, plate flaws, ghost images, or the wings of bright stars. Such objects were eliminated from consideration. The remaining objects were compared with any other frames of the field in question (POSS I, or a neighboring POSS II plate) that were available from STScI. Objects that were visible on a second plate and appeared morphologically like a dwarf galaxy were immediately labeled candidates. Some objects that were not confirmed on additional plates were also added to the candidate list if no other plate was available for comparison or if their morphology was particularly convincing.

4. POSS Search Results

We surveyed 1\deg of sky around each of 264 HVCs. Because some of the HVCs were close together, the total area searched was about 239\deg². Our survey revealed 60 LSB objects, for an overall candidate identification rate of 0.25\deg⁻² of sky searched. Of these, 18 were toward the 59 BB99 compact HVCs (0.31\deg⁻²) in our sample, and five were in the direction of the 17 secondary objects (0.29\deg⁻²). The remaining 37 were found while examining the 188 HVCs from the RB02 catalog (0.20\deg⁻²). The positions of these LSB dwarf galaxy candidates are given in Table 1. For comparison, we also searched (mostly by accident) 54\deg² of sky that were not associated with any known high-velocity gas and found 10 additional LSB features (0.19\deg⁻²). Without even following up on the candidates, we can see that there is not a large excess of them in the direction of HVCs relative to their abundance in random patches of sky. The somewhat higher smudge detection rates for the BB99 HVCs are not statistically significant.

5. Optical Follow-up Observations

5.1. Observing Setup

We obtained follow-up images of each of the candidate dwarf galaxies from Lick Observatory. We observed with the 1 m Anna L. Nickel Telescope for 12 nights between 1999 July and 2000 April. Conditions during these nights were generally close to photometric, although there were occasional clouds, which our observations avoided. The seeing varied from 1\arcsec to 2\arcsec.5. Our primary detector was CCD 5, a 1024 × 1024 thinned SiTe CCD with 24 \( \mu \)m pixels (5\arcsec field of view). However, for two nights during which this instrument was unavailable, we used CCD 2, an older 2048 × 2048 L30 464-5 thick phosphor-coated CCD with 15 \( \mu \)m pixels (7\arcsec field of view).

We also used the 3 m Shane Telescope for deeper follow-up observations. We observed for five nights (2000 April 6–7 and 2000 September 28–30) with the Prime Focus Camera. This instrument utilizes a 2048 × 2048 SiTe CCD with 24 \( \mu \)m pixels to provide a 10\arcsec field of view. These nights also ranged from photometric to partly cloudy, with variable seeing, but again, our observations were not significantly affected by the clouds.

With both telescopes, we chose to employ a Spinrad \( R \) (\( R_g \)) filter for most of our observations. We avoided using standard \( R \) filters because of the extremely strong Na D1 and D2 lines in the Lick Observatory sky, and we felt that \( I \)-band observations would also result in the sky being too...
bright. The $R_S$ filter is centered at 6850 Å, with a FWHM of approximately 1500 Å (somewhat redder, more symmetrical, and wider than Cousins $R$), and was designed specifically to suppress the nearby night-sky emission lines. $R_S$ magnitudes tend to be similar to Johnson $R$ magnitudes, within 0.1 mag for $-0.8 < V-R < 1.8$ (Djorgovski 1985). On the 1 m telescope, we typically observed each object for 1 hr, and on the 3 m for 15–30 minutes. During the course of each night, we observed standard star fields chosen from the Landolt (1992) catalog to obtain photometric calibrations, as described below.

5.2. Data Reduction and Analysis

Most of our data reduction was done in IDL, although we used IRAF\(^6\) for some of the photometry. Processing consisted of subtracting off a dark frame (for the 1 m images) or an overscan region (for the 3 m images), flat-fielding with a twilight or dome flat, and flat-fielding again with a sky flat, if necessary. We removed cosmic rays with the QZAP routine. The frames were then shifted and co-added to yield a single image for each object. We obtained 8–30 standard star observations per night, which we used to construct a photometric solution of the following form,

$$R_S = m_{\text{instr}} + C + f(V-I) + g(a-1),$$

where $R_S$ is the apparent Spinrad $R$ magnitude, $m_{\text{instr}}$ is the instrumental magnitude, $C$ is the constant offset, $f$ is the color coefficient, $V-I$ is the known or assumed Johnson–Cousins color of the object, $g$ is the tabulated Lick mean extinction coefficient,\(^7\) and $a$ is the air mass. Equation (17) from Djorgovski (1985) was used to convert the Cousins $R$ magnitudes that Landolt (1992) measured for the standard stars into Spinrad $R$ magnitudes. (The diligent reader will note that Djorgovski’s eq. [17] actually gives the transformation between Johnson $R$ and $R_S$. This mismatch between the Johnson and Cousins systems could lead to a systematic error of the order of 0.1 mag, which is not large enough to affect our results. An equally important systematic effect is that the optical path and detector combination we used is quite different from that which Djorgovski calibrated in 1985.)

We used a local maximum finding algorithm to detect stars and galaxies in our images. Artificial star tests demonstrated that this algorithm finds essentially all sources that are detected at the 10 $\sigma$ level or higher. Aperture magnitudes were calculated for each of the detected sources with the DAOPHOT package (Stetson 1987) in IRAF. These magnitudes were converted to $R_S$ using equation (1), and assuming that $V-I = 1.1$ (approximately the correct color for the most luminous red giants). Since the color coefficient was usually of the order of 0.1, this estimate can be off by several tenths of a mag without having any appreciable effect.

After locating the sources and deriving their magnitudes, we checked the co-added images for overdensities of point sources around the positions of the dwarf galaxy candidates. We traced out a region of interest around each candidate and compared the surface density of sources inside and outside the regions over various magnitude bins. We considered magnitude ranges starting with all the objects brighter than the magnitude limit and fainter than a tip of the red giant branch (TRGB) star at about 100 kpc: $R_S = 16.5$ (since our survey technique is not sensitive to galaxies closer than this distance). We then decreased the bright limit by 1 mag at a time to create successive bins (see Table 2 for an example). We used Poisson statistics to quantify the uncertainty in the number of stars expected to lie inside the region based on the background surface density. Overdensities of 3 $\sigma$ or higher were considered significant enough to warrant further investigation.

5.3. Results

If there were a resolved dwarf galaxy in the field being examined, one would expect to see an overdensity through all the magnitude ranges. This overdensity would increase

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\(^6\)IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, (AURA), Inc., under cooperative agreement with the National Science Foundation.

\(^7\)See http://www.ucolick.org/~mountain/mthamilton/techdocs/info/lick_mean_extinct.html.
| HVC Name   | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | Point Source Overdensity | Nebular Counterpart | Limiting $R_B$ Magnitude of Follow-up Image | HVC Catalog |
|------------|---------------------|---------------------|--------------------------|--------------------|---------------------------------------------|-------------|
| 104−70−312 | 00 24 36            | −08 09 54           | Yes                      | No                 | 22.3                                        | RB          |
| 120−30−289 | 00 38 34            | 32 43 47            | No                       | No                 | 21.4                                        | BBS         |
| 158−39−280 | 02 40 43            | 16 31 28            | No                       | No                 | 22.1                                        | RB          |
| 169−43−259 | 03 01 38            | 08 14 55            | No                       | No                 | 21.9                                        | RB          |
| 169−40−235 | 03 07 46            | 10 25 00            | No                       | No                 | 22.1                                        | RB          |
| 050+81−442 | 13 29 31            | 29 13 00            | No                       | No                 | 23.4                                        | RB          |
| 046+25−235 | 20 41 02            | −01 16 49           | No                       | No                 | 21.4                                        | RB          |
| 039−33−330 | 20 47 33            | −16 20 36           | No                       | No                 | 21.6                                        | BBS         |
| 040−31−272 | 20 52 21            | −08 17 35           | No                       | Yes                | 21.8                                        | BB          |
| 083−49−307 | 23 09 23            | 05 27 13            | No                       | No                 | 21.1                                        | RB          |
| 083−50−325 | 23 11 24            | 05 17 13            | Yes                      | No                 | 22.2                                        | RB          |
| 107−30−421 | 23 49 28            | 50 57 13            | No                       | Yes                | 22.8                                        | BB          |
| 100−49−395 | 23 50 19            | 10 48 33            | No                       | No                 | 22.9                                        | RB          |
| 104−32+202 | 01 16 23            | 03 47 29            | No                       | Yes                | 21.5                                        | RB          |
| 189−32−248 | 04 25 34            | 13 26 43            | No                       | Yes                | 22.5                                        | RB          |
| 162+14−382 | 06 02 42            | 51 25 53            | No                       | No                 | 22.9                                        | RB          |
| 159+32−268 | 08 03 13            | 58 25 30            | No                       | No                 | 23.3                                        | RB          |
| 204+30−061 | 08 26 44            | 20 15 15            | No                       | No                 | 22.3                                        | BB          |
| 237+50−078 | 10 24 49            | 06 36 41            | Yes                      | No                 | 22.7                                        | BB          |
| 237+51−120 | 10 30 23            | 07 47 05            | No                       | No                 | 22.6                                        | BBS         |
| 039−31−278 | 20 51 55            | −08 26 19           | No                       | No                 | 21.9                                        | BB          |
| 039−33−226 | 21 10 03            | 24 01 16            | No                       | No                 | 20.2                                        | RB          |
| 072−16−395 | 21 15 21            | −11 40 21           | No                       | No                 | 21.8                                        | BB          |
| 079−37−213 | 22 32 37            | 13 10 41            | No                       | No                 | 22.4                                        | RB          |
| 079−37−235 | 22 32 37            | 13 10 41            | No                       | No                 | 22.4                                        | RB          |
| 079−37+252 | 22 32 37            | 13 10 41            | No                       | No                 | 22.4                                        | RB          |
| 080−42−329 | 22 46 29            | 10 09 49            | No                       | Yes                | 22.2                                        | RB          |
| 083−49−307 | 23 09 23            | 05 27 13            | No                       | No                 | 21.1                                        | RB          |
| 083−50−325 | 23 11 24            | 05 17 13            | Yes                      | No                 | 22.2                                        | RB          |
| 050+68−201 | 23 23 12            | −19 09 33           | No                       | No                 | 21.1                                        | BB          |
| 011−07−466 | 23 24 53            | 53 58 00            | No                       | No                 | 22.6                                        | BB          |
| 093−52−312 | 23 38 57            | 35 19 19            | No                       | No                 | 21.3                                        | BB          |
| 093−52−266 | 23 38 57            | 06 09 19            | No                       | No                 | 21.1                                        | RB          |
| 108−21−395 | 23 39 46            | 39 25 39            | No                       | No                 | 20.0                                        | BB          |
| 093−55−276 | 23 43 02            | 04 28 13            | No                       | No                 | 21.5                                        | RB          |
| 080−66−226 | 23 44 55            | 09 15 57            | No                       | No                 | 22.1                                        | RB          |
| 097−53−384 | 23 48 35            | 07 07 42            | No                       | Yes                | 21.5                                        | RB          |
| 107−30−421 | 23 48 55            | 31 28 44            | No                       | Yes                | 22.6                                        | BB          |
| 100−49−395 | 23 50 19            | 10 48 33            | No                       | No                 | 22.9                                        | RB          |
| 104−32+202 | 04 16 23            | 03 47 29            | No                       | Yes                | 21.5                                        | RB          |

**TABLE 1**

The Candidate Dwarf Galaxies Identified in Our Survey
in significance as the bright end of the magnitude bins approached the TRGB of the galaxy, reaching a maximum near the bin where the TRGB was closest to the bright edge of a bin. Visually, a dwarf galaxy should also show an obvious clustering of "undetected" faint stars that do not meet our 10 \( \sigma \) limit for photometry, since the red giant branch is more populated at lower luminosities. We searched each image for point source overdensities of at least 3 \( \sigma \) in one magnitude bin. Eight of the counterparts met this criterion, with the most significant one having a maximum overdensity of \( \sim 11 \sigma \).

As a comparison, we observed the dSphs And III and And V. And III has a total luminosity of \( M_V = -10.2 \) and a central surface brightness of \( \mu_V = 24.49 \) mag arcsec\(^{-2} \), and given its distance of 760 kpc and the Galactic extinction (\( A_R = 0.15 \) mag), the TRGB should be located at \( R = 21.15 \) (Caldwell et al. 1992; Armandroff et al. 1993; Schlegel, Finkbeiner, & Davis 1998). And V is a significantly fainter galaxy, with \( M_V = -9.1 \) and \( \mu_V = 25.01 \) mag arcsec\(^{-2} \), and is slightly farther away and more extincted (810 kpc, \( A_R = 0.33 \) mag), so it should show a red giant branch starting at \( R = 21.48 \) (Caldwell 1999; A98; Schlegel et al. 1998).

Our results for 3 m observations of And III (15 minutes) and And V (21 minutes) are given in Table 2. Based on a comparison between the stellar densities and the background surface density, we detected about 160 stars in And III and 80 in And V. Both galaxies were detected at the 10.9 \( \sigma \) level or higher in every magnitude bin, and the highest overdensities (\( \sim 15–20 \sigma \)) appear in the bins that begin closest to the TRGB magnitudes, matching our expectations. The decreased overdensities seen in the last bin imply that the observations were affected to some degree by crowding or incompleteness at that magnitude level. We also imaged And V for 20 minutes with the 1 m telescope (this exposure was much shorter than any of our observations of dwarf candidates) and detected the galaxy at 4.0 \( \sigma \) in the faintest magnitude bin. This significance level corresponded to 12 stars above the background density over the area of the dwarf galaxy.

Since we detect known dwarf galaxies very easily with typical 3 m observations and weakly with much shorter than average 1 m observations, we can be confident that our observations were sufficient to locate any new galaxies similar to the known ones. Because the strongest candidate detections we made are still weaker than And V, one of the least luminous galaxies known, we also know immediately that if there are any dwarf galaxies associated with HVCs, they are fainter than known dwarfs.

We also found that 15 of the dwarf galaxy candidates appeared to contain faint nebular emission in our follow-up images. We suspect that a number of these are Galactic cirrus clouds. The remaining 37 candidates were not detected in any way during the follow-up observations, so we are forced to assume that these represent flaws on the Palomar plates that happened to have the appearance of dwarf galaxies.
5.4. Comments on Individual Candidates

**HVC 104−70−312.**—At the location of this candidate, we found a 5 \( \sigma \) density enhancement of faint sources, which contains 27 more objects than expected from the background and peaks in significance around \( R_S = 19.3 \). It is higher than 4.5 \( \sigma \) in all but the faintest magnitude bin. The sources appear to be clustered around a bright (\( R_S = 18.9 \)) galaxy near the middle of the region. In our Lick image, it is obvious that most of the sources are within 1' of this galaxy, rather than occupying the full 4' \times 2' \) LSB area identified on the POSS plate. Taking this into account, the overdensity increases in significance to \( \sim 9 \sigma \) (21 more objects than expected). Of the sources brighter than \( R_S = 20.4 \) (2 mag brighter than the detection limit), five out of nine are classified as galaxies on the basis of their radial profiles (FWHM larger than the point-spread function). For the fainter sources, it rapidly becomes impossible to distinguish stars from galaxies, but at least half of the 16 objects between \( R_S = 20.4 \) and 21.4 appear to be stars. Therefore, there may be a group of 15−20 faint (\( R_S \geq 20.4 \)) stars at this position. There are also \( \sim 20 \) objects within 1' of the central galaxy that are visible by eye but are fainter than our software detection limit. Without further observations, we cannot rule out the possibility that this is an exceedingly dim dwarf galaxy (\( M_V \approx -7 \)), but we suspect that other alternatives (e.g., galaxy cluster, random grouping of foreground stars) are more likely.

**HVC 118−58−373.**—Most of the sources associated with this small (11 objects) overdensity appear to be stars. The significance stays almost constant (as does the overabundance by number) down to the 20.6−22.6 bin, in which it reaches a maximum of 3.5 \( \sigma \). However, even with the fairly deep limiting magnitude of this image, there is no hint of numerous fainter stars in the region below our formal 10 \( \sigma \) detection limit, which should of course be present if this were a dwarf galaxy. With so few objects here, the statistics are obviously poor, but we argue that this candidate is probably a chance alignment of foreground stars.

**HVC 171−54−235.**—The overdensity is highest (3.6 \( \sigma \)) in the largest magnitude range and decreases monotonically thereafter. This behavior is not at all what is expected from a dwarf galaxy. Again, there is no sign of “undetected” (less than 10 \( \sigma \)) sources. Since the overabundant objects are bright and are not accompanied by more numerous faint counterparts, this candidate is not a dwarf galaxy.

**HVC 237+50+078.**—This candidate has an overdensity of 25 stars, which peaks at a significance level of 3.1 \( \sigma \) around magnitude 18. The sources are not very centrally concentrated; rather, many of them are in several small groups of about six objects. Of the fraction (about 2/3) that are bright enough to be solidly classified as either stars or galaxies based on their radial profiles, over 60% are galaxies. Thus, the overdensity of stars is small, and there is no reason to suspect that this is a dwarf galaxy.

**HVC 261+49+160.**—This object was the first distant galaxy cluster that we accidentally discovered. We noticed a highly significant (7.8 \( \sigma \)) clustering of “stars” in our Lick 3 m image. Comparison of the SERC-J and Equatorial Red plates confirmed that these objects had red colors. However, the fact that the brightest of the stars appeared to have slightly extended radial profiles relative to the point-spread function of the Lick image raised suspicions that they were actually marginally resolved distant galaxies. G. Illingworth and V. Tran acquired an image of the cluster with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck\(^4\) telescope that supported this interpretation (see Fig. 3), so we obtained spectra of the brighter objects with the Hobby-Eberly Telescope.\(^9\) The spectra revealed that the bright central sources in this field were compact elliptical galaxies at \( z = 0.35 \). Thus, we conclude that this is a cluster of galaxies. (We should point out that technically this position was not listed in either of the HVC catalogs we used; it was only examined by mistake. However, there is actually high-velocity H I emission at this position in the LDS that was too weak to be included in the RB02 catalog. This cloud is also listed in the compilation of Wakker & van Woerden [1991], so it really is an HVC.)

**HVC 143+65+283b.**—This candidate also appeared in a 3 m image as a small clustering of slightly extended objects (23 more than would be expected from the background surface density). We did not obtain spectra, but I-band imaging from the 1 m telescope confirmed that many of these objects have similar colors. The significance of the clustering reaches a maximum of 3.9 \( \sigma \) and begins to fall off around magnitude 19. Of the bright objects in the region, 64% are clearly galaxies, and a 15th magnitude star is also present. These probably combine to explain the source of the LSB emission our algorithm picked up on the POSS plates. We consider this candidate to be a likely galaxy cluster.

**HVC 083−50−325.**—The morphology of this candidate is extremely suggestive of a dwarf galaxy: an elliptical region about 5' across with a very strong concentration of faint point sources (Fig. 4). This was one of the two objects whose overdensities approached those of And III and And V in significance, peaking at 10.8 \( \sigma \). However, a number of the brightest objects are clearly galaxies in our Lick \( R_S \) image, and a significant fraction of those appear to be interacting. We also obtained \( V \)- and \( I \)-band images of this field to aid in classifying the sources in the region of enhanced surface density. Taking into consideration the radial profile, morphology, and color of each source, we classified 62% of the identifiable objects as galaxies. Many of the galaxies were concentrated in color-color space around \((V−I=2.0, I−R=1.1)\) and also near \((1.5, 0.7)\). Furthermore, an Abell cluster (2545) with a photometric redshift of 0.17 (Gal et al. 2000) is located 20' away from this position, increasing the probability that other clusters are in the vicinity. We feel safe in concluding that this candidate is another cluster of galaxies at moderate redshift.

**HVC 107−30−421.**—We found a small (\( \sim 1' \)), elongated, very faint nebula north of the center of this HVC on the Palomar plates. A deep exposure on the 1 m telescope confirmed the reality of the source, but its extremely low surface brightness (\( \mu_R \approx 25.3 \text{ mag arcsec}^{-2} \)) made it difficult to classify. A. Bunker, S. Dawson, A. Dey, H. Spinrad, and D. Stern obtained an \( R \)-band image for us with Keck/LRIS, which revealed more structure in the object but definitely

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\(^{4}\) The W. M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

\(^{9}\) The Hobby-Eberly Telescope is a joint project of the University of Texas at Austin, Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen.
Fig. 3.—Keck/LRIS $I$-band image of the dwarf galaxy candidate 261+49+160, acquired for us by G. Illingworth and V. Tran. The exposure time was 10 minutes (in nonphotometric conditions), and the image has a limiting magnitude of about $I = 21.5$. The concentration of objects in the center of the frame is a spectroscopically confirmed galaxy cluster at $z = 0.35$.

Fig. 4.—Lick 3 m Spinrad $R$ image of the candidate 083−50−325. This 15 minute exposure has a 10σ limiting magnitude of $R_\text{K} = 22.2$. The main concentration of objects that is described in the text includes several bright, interacting galaxies and is centered near R.A. offset = 1′3, decl. offset = −0′2. The overdensity continues less strongly to the northeast, all the way to the top left corner of the image.
6. DISCUSSION

6.1. Expected Red Giant Populations

We were unable to find any mention in the literature of the $R$-band magnitude of the TRGB. However, we can use theoretical studies of stellar evolution to make a reasonable estimate of its location. Girardi et al. (2000, hereafter G00) and Yi et al. (2001, hereafter Y01) both present stellar models that predict TRGB magnitudes of $M_R \approx -3.4$, varying only slightly with age and metallicity within the ranges that interest us. For example, in their $[\text{Fe}/\text{H}] = -1.7$ models, Y01 find a maximum shift of 0.086 mag in the TRGB magnitude for stars ranging in age between 4 and 15 Gyr. G00 give the maximum shift as 0.020 mag for the same parameters. Likewise, in changing metallicities at a fixed age (10 Gyr), the TRGB magnitude varies by only 0.144 and 0.068 mag, according to Y01 and G00, respectively (over most of the range covered by known dSphs, $-2.3 \leq [\text{Fe}/\text{H}] \leq -1.3$). Given what is known about the TRGB in the $V$ and $I$ bands (Lee, Freedman, & Madore 1993), these values seem reasonable, but we can compare them with observations as a further test. One of the few published data sets involving $R$-band observations of a large, homogeneous population of red giants is the study of the Fornax dSph by Stetson, Hesser, & Smecker-Hane (1998). Using their data and an assumed distance modulus for Fornax of 20.70 mag (Beauchamp et al. 1995; Saviane, Held, & Bertelli 2000), we derive a TRGB magnitude of $M_R = -3.3$. Fornax has a high metallicity for a dSph of $[\text{Fe}/\text{H}] = -1.0$ (Saviane et al. 2000), so we should not be surprised that it has a slightly fainter tip magnitude than the models give. We conclude that $M_R = -3.4$ is the best guess for the TRGB magnitude in a typical Local Group dSph.

We noted in § 5.3 that our observations of dSph companions of Andromeda detected ~100 stars in each galaxy. Other recent studies of distant Local Group dwarfs have measured similar or larger numbers of stars within 1 mag of the TRGB: ~100 such stars in And VI (Armandroff et al. 1999), ~200 stars in And VI and ~650 stars in And VII (Grebel & Guhathakurta 1999), 156 stars (including some asymptotic giant branch contamination) in Phoenix (Held, Saviane, & Momany 1999), and 77 stars in Tucana (Saviane, Held, & Pietro 1996). Since typical background surface densities in our images are ~8 stars arcmin$^{-2}$ (varying strongly with Galactic latitude) and these densities are a factor of a few higher, such objects are easily detected. Their absence in our survey indicates that HVCs do not contain dwarf galaxies with typical parameters ($M_V \lesssim -9$, $\mu_V \lesssim 25.0$ mag arcsec$^{-2}$).

6.2. Distance and Surface Brightness Limits

Our follow-up observations of dwarf galaxy candidates reached 10 $\sigma$ limiting $R_0$ magnitudes between 20.0 and 23.4, with a median value of 22.2. We can convert these limiting magnitudes into a minimum distance at which a dwarf galaxy would have to lie in order to have escaped detection. If we assume that these observations must probe 1 mag below the TRGB in order to detect a dwarf galaxy, then the limiting distance is

$$d_{\text{lim}} = 10^{(m_{\text{lim}} + 7.4)/5} \text{ pc}.$$
For the minimum, median, and maximum limiting magnitudes we achieved, this distance corresponds to 302, 832, and 1445 kpc, respectively. These distance limits are quite conservative, because we have insisted that stars be detected at 10 \( \sigma \) (even though they can be visually identified in images at significantly fainter levels), and because objects as bright as the known dSphs can easily be located on images that reach less than 1 mag below the TRGB. Therefore, we can state with confidence that none of the candidate dwarf galaxies are actually dwarfs within 100–300 kpc of the Milky Way, and all but two would have to be several times farther away to have been missed.

The depth of the POSS II portion of our search is more difficult to assess. The Palomar data are not of uniform sensitivity: exposure times vary by up to a factor of 2 from plate to plate, and on a single plate there is significant vignetting within \( \sim 1' \) of the edges. Furthermore, different parts of the sky are covered by different photographic surveys. Distant Local Group galaxies (\( \gtrsim 200 \) kpc) are not resolved and appear in the Palomar data as smudges with higher surface brightnesses than the surrounding areas. Because all the distant dSphs are visible by eye on the Palomar plates, we know that the POSS II is sensitive down to at least \( \mu_V = 25.0 \) mag arcsec\(^{-2} \). Using the stellar evolution models discussed in § 6.1 again, we estimate that these galaxies should have colors around \( V - R = 0.5 \). Thus, the \( R \)-band sensitivity of the Palomar images (since we used the red plates wherever possible) is better than \( \mu_R = 24.5 \) mag arcsec\(^{-2} \).

A few dSphs are known to have surface brightnesses lower than these levels. Some of the Milky Way companions at \( d < 100 \) kpc have \( 25.3 \leq \mu_V \leq 26.2 \) mag arcsec\(^{-2} \) (i.e., Carina, Draco, Sextans, Ursa Minor, and Sagittarius). Out of these, Carina and Draco are visible by eye in POSS II images, and the others are detectable via star counts. Since galaxies this close are resolved into individual stars on POSS plates, it is not entirely clear how to consider them with regard to a limiting surface brightness. Nevertheless, all Local Group galaxies with \( \mu_V < 25.5 \) mag arcsec\(^{-2} \) are visible, and one of the two galaxies with \( \mu_V = 25.5 \) mag arcsec\(^{-2} \) can also be seen visually. Thus, the naked-eye sensitivity of the red POSS II plates is likely to be \( \mu_V = 25.5 \) mag arcsec\(^{-2} \), or \( \mu_R = 25.0 \) mag arcsec\(^{-2} \). Our processing routine should improve these values, perhaps by \( \sim 0.5 \) mag. Therefore, we estimate that our survey is able to find galaxies down to \( \mu_V = 26.0 \) mag arcsec\(^{-2} \), or \( \mu_R = 25.5 \) mag arcsec\(^{-2} \). (It is worth noting that foreground Galactic extinction prevents us from quite reaching these limits; the median \( A_R \) for HVCs in our sample is 0.18 mag [Schlegel et al. 1998]).

6.3. Implications

The fact that our survey did not detect any new dwarf galaxies toward the \( \sim 250 \) HVCs that we examined rules out the hypothesis that HVCs are the gaseous components of normal, but faint, Local Group dwarf galaxies. If these HVCs do contain stars, they must have central surface brightnesses \( \mu_V \gtrsim 26 \) mag arcsec\(^{-2} \). They are also likely to have absolute magnitudes \( M_V \gtrsim -9 \), although a very extended stellar counterpart with an extremely low surface brightness could yield a higher total luminosity while still escaping detection. Even though it is conceivable that a few objects could have been missed because of our survey design, on the whole it seems clear that HVCs are starless systems.

Known Local Group dwarfs do have surface brightnesses as faint as \( \mu_V = 26.2 \) mag arcsec\(^{-2} \), but only a handful of the

![Fig. 6.—Relationship between luminosity and surface brightness for spheroidal galaxies, dSphs, and the so-called transitional (dSph/Irr) galaxies in the Local Group (Pegasus and Phoenix are not included in this figure because they lack published surface photometry data). The only known dwarfs with \( \mu_V > 25.05 \) mag arcsec\(^{-2} \) (to the left of the dashed line) are the Milky Way satellites within 100 kpc. All the M31 companions and isolated dwarfs in the Local Group have higher surface brightnesses. The data used to make this plot were taken from tables compiled by Mateo (1998) and van den Bergh (1999, 2000) (see references therein for the original sources), except for the surface photometry for DDO 210, which was adapted from Lee et al. (1999).]
very extended Milky Way satellites are in this range (see Fig. 6). Surveys of nearby groups and clusters confirm that dSphs with \( \mu_V \geq 26 \) mag arcsec\(^{-2} \) either do not exist or cannot be detected with current techniques (Caldwell & Bothun 1987; Impey, Bothun, & Malin 1988; Bothun, Schombert, & Caldwell 1989; Bremses, Binggeli, & Prugniel 1998; Caldwell et al. 1998; Jerjen, Binggeli, & Freeman 2000; Karachentsev et al. 2000, 2001). For the distant Local Group dSphs (Andromeda companions and isolated galaxies), the lowest surface brightness is \( \mu_V = 25.05 \) mag arcsec\(^{-2} \) for Cetus and Tucana. All of these distant galaxies are visible in the POSS II data and are easily detected by both our POSS processing algorithm and our follow-up imaging campaign. Thus, we are confident that any objects similar to known dSphs would have been discovered in our survey if they were present. Lower surface brightness stellar counterparts could be present, but the fact that no such systems (with or without \( \text{H}_\text{I} \) components) are known argues against this possibility. We believe that the most likely explanation for our findings is that HVCs simply do not contain stars.

This result does not lead to the anticipated outcome of our survey: a means of discriminating between HVC models. In the Galactic fountain and tidal debris models, stars would not be expected to form in HVCs, in agreement with our finding. However, although the Local Group model certainly allows for stars in HVCs and, we would argue, suggests that stellar counterparts are likely, it does not require them. Therefore, while a positive result in our search would have strongly supported the Local Group model, the inverse is not necessarily the case. As mentioned earlier, Bullock et al. (2000) and others have proposed ideas explaining how small dark matter halos scattered throughout the Local Group could contain some neutral gas without having formed stars. We believe that the absence of stars may be an important clue to the nature of HVCs, but by itself, it does not allow us to solve the puzzle.

6.4. Compatibility with Previous Work

There have been no other comprehensive and quantitative searches for evidence of stars in HVCs. Ivezic & Christodoulou (1997) examined \textit{IRAS} data toward the large HVC complexes in an effort to locate any star formation that might be occurring but only came up with one possible young star in positional coincidence with high-velocity \( \text{H}_\text{I} \). BB99 searched DSS images in the direction of each of their compact HVCs but found no clear optical counterparts, and J. Simon et al. (in preparation) used infrared- and millimeter-wave observations to search for a stellar counterpart to complex H, with null results. Thus, the result of this work is entirely compatible with the data existing in the literature.

7. CONCLUSIONS

We have surveyed 1 deg\(^2 \) of sky around each of 264 high-velocity clouds in search of new Local Group dwarf galaxies. We processed digital POSS I and POSS II images with an algorithm to enhance LSB features. We then examined the images and found 60 faint smudges that we classified as possible Local Group dwarfs. Using the 1 m and 3 m telescopes at Lick Observatory, we imaged each of these candidates to a typical limiting stellar magnitude of \( R_s = 22.2 \). Examination of the data revealed several \( \geq 3 \sigma \) density enhancements of faint sources in the areas selected from the POSS plates, but none of these appear to be Local Group dwarf galaxies. Typical faint Local Group dSphs would have been detected at the \( \geq 10 \sigma \) level, with \( \sim 100 \) stars brighter than the detection limit. Therefore, we conclude that there are no undiscovered normal dwarf galaxies within a 30' radius of any of these HVCs, provided that the HVCs are located at least 100 kpc from the Milky Way; dwarf galaxies at a smaller distance might be too diffuse to detect in this manner.

There were both observational and theoretical grounds for suspecting that compact HVCs might harbor faint LSB dwarf galaxies. It is well known that the highly successful cold dark matter theory predicts large numbers of small dark matter halos, which have not yet been detected observationally. Klypin et al. (1999) and others have pointed out that HVCs are numerous enough (and massive enough, in the Local Group picture) to comprise the set of missing halos. From the observational side, Blitz & Robishaw (2000) noted that there are similarities between the \( \text{H}_\text{I} \) components of Local Group dwarfs and the properties of HVCs, if they are located at typical distances from the Milky Way of \( \sim 700 \) kpc. Furthermore, blind \( \text{H}_\text{I} \) surveys of nearby groups of galaxies often find that the \( \text{H}_\text{I} \) clouds they detect are associated with LSB dwarfs.

The implications of our observation that Local Group \( \text{H}_\text{I} \) clouds lack such stellar counterparts are unclear. While this finding does not rule out the Local Group hypothesis for the spatial distribution of the HVCs, it also does not provide any supporting evidence. We are still unable to constrain HVC distances, but we have placed significant limits on their stellar content. Regardless of the location of the HVCs, as long as they are at least 100 kpc away, either they lack stars entirely, or they have lower surface brightnesses and luminosities than other systems in the Local Group.

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