

H I IMAGING OF LGS 3 AND AN APPARENTLY INTERACTING HIGH-VELOCITY CLOUD

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ABSTRACT

We present a $93' \times 93'$ map of the area near the Local Group dwarf galaxy LGS 3, centered on an H I cloud $30'$ away from the galaxy. Previous authors associated this cloud with LGS 3 but relied on observations made with a $36'$ beam. Our high-resolution (3.4), wide-field Arecibo observations of the region reveal that the H I cloud is distinct from the galaxy and suggest an interaction between the two. We point out faint emission features in the map that may be gas that has been tidally removed from the H I cloud by LGS 3. We also derive the rotation curve of the cloud and find that it is in solid-body rotation out to a radius of $10'$, beyond which the rotation velocity begins to decline. Assuming a spherical geometry for the cloud, the implied mass is $2.8 \times 10^7 (d/\text{Mpc}) M_{\odot}$, where d is the distance in Mpc. The observed H I mass is $5.5 \times 10^6 (d/\text{Mpc})^2 M_{\odot}$, implying that the cloud is dark matter dominated unless its distance is at least 1.9 Mpc. We propose that the cloud is a high-velocity cloud that is undergoing a tidal interaction with LGS 3 and therefore is located roughly 700 kpc away from the Milky Way. The cloud then contains a total mass of $\sim 2.0 \times 10^7 M_{\odot}$, 82% of which consists of dark matter.

Subject headings: dark matter — galaxies: dwarf — galaxies: individual (LGS 3) — galaxies: interactions — Local Group — radio lines: galaxies

1. INTRODUCTION

The biggest challenge facing studies of high-velocity clouds (HVCs) is that their distances and masses are almost completely unknown. We attack this problem by using the upgraded Arecibo telescope to completely map a large area (2.4 deg^2) around the Local Group dwarf galaxy LGS 3 and a newly identified HVC. If the HVC and the dwarf galaxy are interacting, as we will argue, then this system presents a unique opportunity to constrain the distance and mass of an HVC.

The H I cloud next to LGS 3 appears to have been first detected by A. Hulsbosch in 1982 using the Dwingeloo 25 m telescope (Christian & Tully 1983). Hulsbosch & Wakker (1988) listed the cloud in three entries in their HVC survey, at $(l, b, v_{\text{LSR}} [\text{km s}^{-1}]) = (127^{\circ}, -41^{\circ}, -331)$, $(128^{\circ}, -41^{\circ}, -329)$, and $(127^{\circ}, -42^{\circ}, -352)$, all of which they consider to be part of LGS 3, which is located at $(l, b, v_{\text{LSR}} [\text{km s}^{-1}]) = (126^{\circ}75', -40^{\circ}89', -287)$. The original H I observations of LGS 3 by Thuan & Martin (1979), made using Arecibo, did not detect the cloud because they were directed at the optical position of the galaxy rather than $30'$ away. Christian & Tully (1983) noted the clear velocity gradient across the cloud, but they were unable to draw any conclusions about the nature of the cloud from the $36'$ resolution observations. The cloud was also seen in the Leiden/Dwingeloo Survey (LDS) of Galactic Neutral Hydrogen (Hartmann & Burton 1997) and was found by Blitz & Robishaw (2000) to be substantially larger in both area and H I mass (if at the same distance as the galaxy) than LGS 3 itself. Blitz & Robishaw (2000) further noticed that the velocity of the cloud was different from that of the dwarf galaxy by -50 km s^{-1} and postulated that the cloud could have been removed from LGS 3 by ram-pressure stripping. However, they also argued that the HVC should have a less negative velocity than the dwarf galaxy in the case of ram-pressure stripping, making this interpretation doubtful.

In § 2, we describe our observations and discuss the data reduction. Our analysis of the data is presented along with our map of the HVC and its rotation curve in § 3. In § 4, we discuss

our results and evidence for a possible interaction between the HVC and LGS 3.

2. OBSERVATIONS AND DATA REDUCTION

The observations were conducted over five nights in 2000 November using the upgraded Arecibo telescope.¹ We employed the L-band narrow receiver and the 9 level, dual-polarization correlator configuration to yield spectra with a velocity resolution of 0.644 km s^{-1} . At the frequency of H I observations, the telescope has a half-power beamwidth of 3.4 , a main-beam efficiency of 0.48 , and a gain of 7.2 K Jy^{-1} (Heiles 2000).

The data we present in this paper include three nights of on-the-fly (OTF) maps, Nyquist sampled in right ascension and declination, and two nights of drift scans. The OTF maps cover a $93' \times 93'$ region, and the drift scans add sensitivity in a $40' \times 40'$ area between and including the HVC and LGS 3. The integration time was $\sim 22 \text{ s beam}^{-1}$ for most of the map and $\sim 92 \text{ s beam}^{-1}$ in the area covered by the drift scans. We reached rms sensitivity levels at the full velocity resolution of 75 and 34 mK beam^{-1} in those regions, respectively.

Each night we observed a single off-source position, which we used to remove the bandpass shape for all of the spectra from that night. Gain calibration was provided by the injection of a known signal into the correlator once per strip. We fitted and removed a linear baseline from each spectrum. We developed a new algorithm to remove spectral standing waves that were present in the data. The drift scans were resampled to match the sampling of the OTF maps, and we then co-added each night's observations to form a single data cube. The reduction will be described in more detail in a future paper presenting the results of our survey of 27 HVCs and Local Group dwarf galaxies.

¹ The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation.

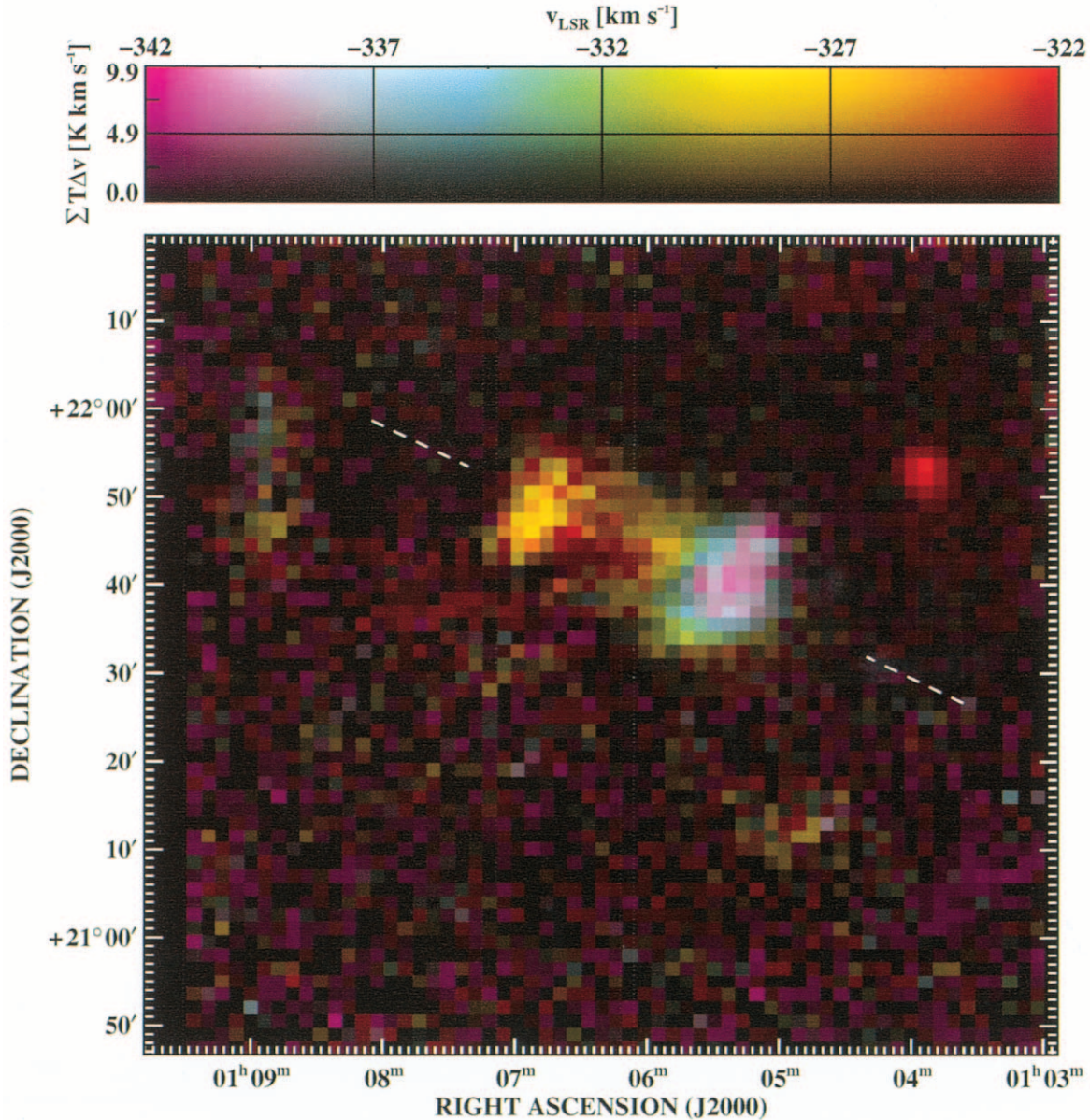


FIG. 1.—High-resolution H I map of HVC and LGS 3. The image, in which color represents velocity and intensity represents column density, consists of ~ 10 hr of on-source integration time acquired over the course of five nights. The pixel size is $1''.5$, or slightly less than half of a beamwidth. Visible in the map are the Local Group dwarf galaxy LGS 3 [the bright red object at $(\alpha, \delta) = (01^{\text{h}}03^{\text{m}}54^{\text{s}}, +21^{\circ}53')$ (J2000.0) in the upper right], a compact HVC (the large double-lobed cloud in the center) with a 14 km s^{-1} gradient across it, and two faint features (to the left and lower right of the HVC) that we believe are remnants of a tidal interaction between LGS 3 and the HVC. The dashed white line shows the major axis of the HVC.

3. RESULTS

Our map (Fig. 1) reveals considerable detail that was not apparent in previous observations. The H I associated with LGS 3 is visible in the upper right (northwest) as the small red blob at $(\alpha, \delta) = (01^{\text{h}}03^{\text{m}}54^{\text{s}}, +21^{\circ}53')$ (J2000.0). The emission is marginally resolved spatially and has an intensity-weighted mean LSR velocity of -287 km s^{-1} . We measure an integrated H I flux of $2.3 \pm 0.5 \text{ Jy km s}^{-1}$, in agreement with the value of $2.7 \pm 0.2 \text{ Jy km s}^{-1}$ measured by Young & Lo (1997). For a distance of 700 kpc ,² the H I mass of LGS 3 is $2.6 \times 10^5 M_{\odot}$.

² Three previous authors have measured distances to LGS 3 of very close to 800 kpc : 810 (Lee 1995), 770 (Aparicio, Gallart, & Bertelli 1997), and 830 (Mould 1997). However, in a recent paper based on *Hubble Space Telescope* data, Miller et al. (2001) derive a distance of $620 \pm 20 \text{ kpc}$. We adopt an intermediate distance of 700 kpc for all calculations.

The extended emission seen previously (Christian & Tully 1983; Hulsbosch & Wakker 1988; Blitz & Robishaw 2000) now appears as a large, double-lobed H I cloud in the center of the map with a systemic velocity of $-331.3 \pm 1.0 \text{ km s}^{-1}$, an integrated flux of $24 \pm 8 \text{ Jy km s}^{-1}$, and a mean line width of 24 km s^{-1} . This cloud is completely separate from LGS 3, located $30'$ away with a velocity difference of -45 km s^{-1} . If the cloud is at the distance of LGS 3, it contains 10 times as much H I, making it unlikely that it originated in LGS 3. Therefore, this cloud qualifies as an HVC.

Although LGS 3 and the HVC may not share a common origin, their apparent proximity demands that we investigate the possibility of an interaction between them. To the east of the HVC, at $(\alpha, \delta) = (01^{\text{h}}08^{\text{m}}56^{\text{s}}, +21^{\circ}53')$ (J2000.0), a faint vertical strip of H I extends for $\sim 20'$ along the edge of the

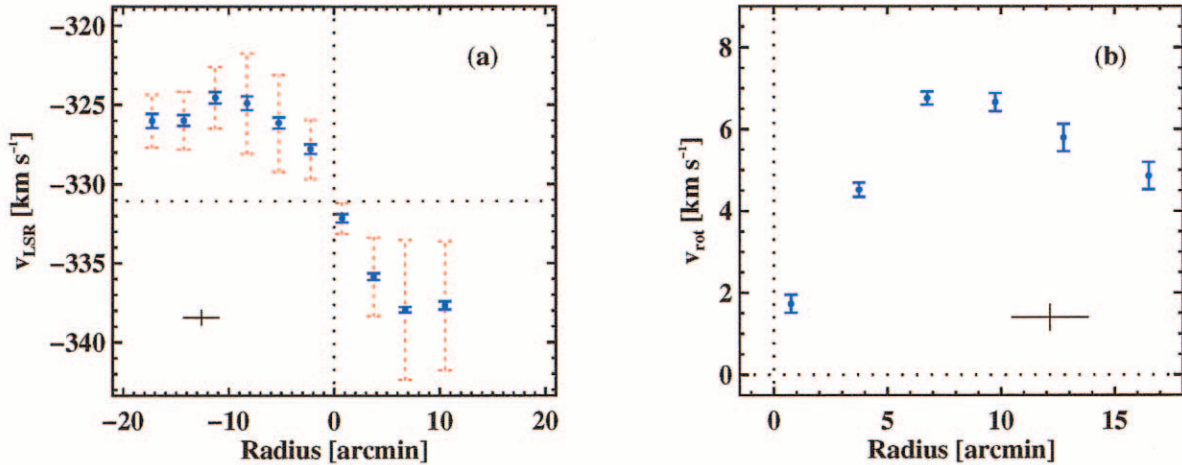


FIG. 2.—(a) The rotation curve along the major axis of the HVC. The point of maximum symmetry is shown by the dotted lines and occurs at $(\alpha, \delta) = (01^{\text{h}}05^{\text{m}}49^{\text{s}}, +21^{\circ}42')$ (J2000.0) with a systemic velocity of $-331.3 \pm 1.0 \text{ km s}^{-1}$. Blue error bars represent the 1σ uncertainty in the velocity of the fitted Gaussian; red dotted error bars represent the rms of the velocity field perpendicular to the major axis. Removing this rotation curve from the velocity field yields a residual field with an rms of 3 km s^{-1} . (b) The rotation curve folded about the point of maximum symmetry. After a solid-body rise out to a radius of $10'$, the rotation curve begins to decrease. The error bars are the 1σ uncertainties of the weighted average of the Gaussian fits. The crosses indicate the velocity and spatial resolution of our measurements.

map. A similar feature is also visible running horizontally in the southwest at $(\alpha, \delta) = (01^{\text{h}}05^{\text{m}}00^{\text{s}}, +21^{\circ}13')$ (J2000.0). The symmetrical placement of this gas relative to the line connecting LGS 3 and the HVC is suggestive of a tidal interaction, with the two faint clouds representing leading and trailing tidal arms. We consider this idea further in § 4.

The most striking feature of the HVC is the velocity gradient across it. We examined the gradient by averaging spectra perpendicular to the major axis. We fitted a Gaussian profile to the averaged spectrum at each point along the major axis to create a rotation curve, which is displayed in Figure 2a. The rotation curve contains a roughly linear gradient over its central $20'$ and then turns over. The turnover and the overall symmetry of the rotation curve suggest that the HVC is a single, rotating, gravitationally bound object and is not composed of two physically distinct clouds that happen to coincide along the line of sight. In order to measure a symmetric rotation curve from two separate clouds, they would have to have the same extent, have the same large aspect ratio, be aligned along their major axes, and have their velocity fields vary with radius in just such a way as to mimic the appearance of a single rotating cloud. We consider this, although not impossible, very unlikely. We further point out that if the HVC were composed of two overlapping clouds, then the line widths would be largest at the center of the HVC. Since we observe exactly the opposite, we conclude that the HVC must be a single cloud.

We can therefore use the rotation curve to compare the dynamical mass of the HVC to its luminous mass, which we assume consists only of H I and a cosmic abundance of He, such that $M_{\text{lum}} = 1.3M_{\text{H I}}$. The dynamical mass (M_{dyn}) is the mass required to account for the rotational velocity of the HVC at the last measured point (see Fig. 2b). The H I mass scales as the square of the distance to the HVC, $M_{\text{H I}} = 5.5 \times 10^6 (d/\text{Mpc})^2 M_{\odot}$, which is $2.7 \times 10^6 M_{\odot}$ for a distance of 700 kpc. The dynamical mass, however, scales linearly with distance, $M_{\text{dyn}} = 2.8 \times 10^7 (d/\text{Mpc}) M_{\odot}$, yielding $2.0 \times 10^7 M_{\odot}$ at 700 kpc. (Note that we assume that the rotation is seen edge-on; if this is not the case, then the actual dynamical mass will be larger by a factor of $1/\sin^2 i$.) Therefore, if the HVC is indeed self-

gravitating, as is suggested by its rotation curve, and it is located at the distance of LGS 3, it must be composed mostly of dark matter (82%). Furthermore, if the cloud is assumed to be any closer than LGS 3 (and is self-gravitating), the ratio of its dynamical mass to luminous mass ($M_{\text{dyn}}/M_{\text{lum}}$) must be even larger; if the cloud is further than LGS 3, it remains dark matter dominated out to a distance of 1.9 Mpc. Since the darkest known galaxy-sized objects have $M_{\text{dyn}}/M_{\text{lum}} \lesssim 100$ (see Mateo 1998 and references therein), we can place a firm lower limit on the distance to the HVC of 39 kpc.

4. DISCUSSION

Is the HVC indeed interacting with LGS 3? We can approach this question by considering the likelihood that these two objects are completely unrelated. Putman et al. (2002) find that compact HVCs cover $\lesssim 1\%$ of the southern sky. De Heij, Braun, & Burton (2002) use an automated analysis of the LDS to measure a similar covering fraction for $\delta \gtrsim -30^{\circ}$. There are indications in the de Heij et al. (2002) catalog of a factor of ~ 2 overdensity of compact HVCs within 20° of LGS 3, which is not surprising because M31 and the Local Group barycenter are located in the same direction as LGS 3.

We estimate the probability of a spatial coincidence between a dwarf galaxy and a compact HVC by considering the number of compact HVCs and dwarf galaxies near LGS 3. For example, within 20° of LGS 3, there are five dwarf spheroidal galaxies and 14 compact HVCs from the de Heij et al. (2002) catalog. The HVC discussed in this paper is located $\sim 30'$ away from LGS 3, so we take a circle of radius $30'$ around each of the nearby dwarfs. Now, the probability that at least one of the compact HVCs lies within one of these circles is $p \approx N_{\text{CHVC}} \Omega_{\text{dwarfs}} / \Omega_{20}$, where N_{CHVC} is the number of compact HVCs contained in the region, Ω_{dwarfs} is the solid angle subtended by the circles around the five dwarf galaxies, and Ω_{20} is the solid angle subtended by the region within 20° of LGS 3. This probability is 4.4%. If we increase the region under consideration to within 60° of LGS 3, there are 10 dwarf spheroidals (including the small dwarf irregulars WLM and Pegasus) and 46

compact HVCs, and the probability of a chance coincidence is 3.5%. Including the probability of the velocities coinciding within 50 km s^{-1} will make the overall probability of such a configuration even lower. However, since these values are not negligibly small, we cannot dismiss the possibility of a chance superposition entirely. Nevertheless, we conclude the HVC is probably at the same distance as LGS 3.

Another piece of evidence that the HVC is not associated with the Milky Way is its extremely large velocity with respect to the Galactic Standard of Rest (GSR) of $v_{\text{GSR}} = -200 \text{ km s}^{-1}$. An object originally associated with the Galaxy (e.g., in a Galactic fountain) would have difficulty acquiring such a high velocity. This velocity also renders a distance beyond the Local Group implausible.

Could this object be another dwarf galaxy interacting with LGS 3, rather than an HVC? Simon & Blitz (2002) searched most of the compact HVCs in the northern hemisphere and concluded that they do not contain stellar counterparts similar to the known Local Group dwarf galaxies. There is no obvious counterpart to this HVC on the Second Palomar Observatory Sky Survey³ plates. We used the techniques of Simon & Blitz (2002) to search more carefully and found a very faint low surface brightness feature nearby. However, follow-up imaging with the Lick 3 m telescope revealed that there is no distant stellar population here. Therefore this cloud, like all other compact HVCs, appears to be a pure gas cloud.

On the basis of our data, we suggest that the faint features to the east and south of the HVC are remnants of a tidal interaction between the HVC and LGS 3. We now consider the consequences of such a situation. The total mass of LGS 3 (derived from its central velocity dispersion) is $1.3 \times 10^7 M_{\odot}$ (Mateo 1998). Hence, its tidal field becomes comparable to the surface gravity of the HVC if the HVC orbit has a minimum approach of $\sim 4 \text{ kpc}$. If the faint features are tidal in origin, the orbit of the HVC is strongly constrained. Since the gravity of LGS 3 is not enough to bind the system—the escape velocity of LGS 3 is $\sim 19 \text{ km s}^{-1}$, while the relative velocity between LGS 3 and the HVC is $\geq 50 \text{ km s}^{-1}$ —the encounter between

them must be a one-time event. The existence of the tidal tails implies that they have already made their closest approach. Given their relative velocity and their projected separation of 5.8 kpc , such an approach would have taken place $\sim 10^8 \text{ yr}$ ago.

5. CONCLUSIONS

We have presented high-resolution H I observations of a 2.4 deg^2 area including the Local Group dwarf galaxy LGS 3 and a previously unresolved cloud of gas adjacent to the galaxy. Our data show that the H I cloud is $30'$ away from the galaxy, with a velocity difference of -45 km s^{-1} , and that they do not appear to be connected. If they are at the same distance, the cloud contains 10 times as much H I and twice as much total mass as LGS 3. Optical imaging of the cloud revealed no stellar counterparts. We therefore argue that the cloud is an HVC, and should not be considered part of the H I component of LGS 3. However, the H I morphology does suggest that an interaction is occurring.

We propose that the faint thin strips of gas on either side of the HVC are tidal arms produced by a close encounter with LGS 3. We note that the probability of a line-of-sight coincidence between the two objects, if they are at different distances, is $\sim 4\%$. We therefore suggest that the most likely interpretation of this system is that LGS 3 and the HVC are at the same distance and have recently undergone a tidal interaction.

We also examine the rotation curve of the HVC, which exhibits a linear increase with radius out to $10'$ and then begins to decrease. Under the assumption that the HVC is self-gravitating, which is supported by the rotation curve's symmetry and turnover at large radii, we use the dynamical mass and the H I mass to derive a lower distance limit for the HVC. For $M_{\text{dyn}}/M_{\text{lum}}$ to be ≤ 100 , the HVC must be at least 39 kpc away if it is self-gravitating. The extremely negative v_{GSR} of the HVC constrains it to be within the Local Group. This HVC is thus unique in that there is evidence that it is both dark matter dominated and physically associated with an object at a known distance.

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