May 2017

Almost Dark Galaxies: The Search for Optical Counterparts

Quinton O. Singer

Macalester College, qsinger@macalester.edu

Abstract

Presented in this paper are results from neutral hydrogen (HI) imaging and analysis of the "Almost Dark" galaxies AGC 219533, AGC 227982, and AGC 268363 using new, higher resolution observations from the Very Large Array (VLA). Selected from the ALFALFA survey, "Almost Dark" galaxies possess significant HI reservoirs but, when the HI data is compared to survey-depth ground-based optical imaging, their optical stellar counterparts have extremely low surface brightnesses. AGC 219533 is one such object. The other two sources, AGC 227982 and AGC 26833, were candidate dark galaxies, as no stellar counterpart was identified in initial ALFALFA optical matching, and as such they possessed some of the most extreme levels of suppressed star formation amongst the isolated sources in the ALFALFA catalog. The new multiconfiguration, high angular (~20") and spectral (1.7 km/s) resolution HI observations presented here have produced spatially resolved column density and velocity distribution moment maps where the HI has been localized. HI masses are derived from VLA flux integral values and ALFALFA distance estimates, and are consistent with those derived from ALFALFA fluxes. Comparison of our resolved HI observations to Sloan Digitized Sky Survey (SDSS) optical images reveals previously unknown optical components for AGC 227982 and AGC 268363, and confirms the association with a very low surface brightness stellar counterpart for AGC 219533. These new results eliminate the three galaxies' candidacy as dark galaxies.

Follow this and additional works at: http://digitalcommons.macalester.edu/mjpa

Part of the External Galaxies Commons, and the Physics Commons

MACALESTER COLLEGE

1. INTRODUCTION

The "Almost Dark" galaxies are identified in data from the Arecibo Legacy Fast Arecibo L-band Feed Array (ALFALFA) survey. ALFALFA is the largest comprehensive survey to date of neutral hydrogen (HI) line emission in the local universe, covering a 7000 square degree area of the sky between $0°$ and $36°$ declination (Haynes et al. 2011). Upon identifying a significant source of HI line emission, ALFALFA catalogs the source's properties and matches it to an optical stellar counterpart, as the presence of HI corresponds with the presence of stars. Since its inception, ALFALFA has detected tens of thousands of HI sources, and when Haynes et al. (2011) released the 40% ALFALFA catalog consisting of 15,855 detections, >98% could be matched to stellar optical components. This leaves <2% of detections which could not be matched. Cannon et al. (2015) finds that 75% of these unmatched detections are likely tidal in origin, which accounts for their dim or nonexistent stellar structure.

The remaining detections constitute potential "dark galaxies," as they are seemingly isolated and thus their origins and behavior are unknown. Dark galaxies are those which possess the HI reservoirs necessary for star formation, but which exhibit some of the most suppressed star formation rates and largest HI mass-to-luminosity ratios (M_{HI}/L_B) ever observed (Cannon et al. 2015). A discovery of a true dark galaxy would challenge current galactic evolution models, as we expect to see stars where we see significant HI sources. Follow-up observations that characterize the HI components of the galaxies at high spatial and angular resolutions are necessary to determine the nature of these objects—particularly, what gives rise to the lack of corresponding stellar structure.

As part of the follow-up observation campaign, the three Almost Dark sources were imaged: AGC 219533, AGC 227982, and AGC 268363. Prior to this work, ALFALFA had derived global HI characteristics for each of these sources. These results can be found in Table 1.

The HI mass of AGC 219533 seen in Table 1 is comparable to that of a typical spiral. The Milky Way, for instance, has a HI mass of roughly $8\times10^9 M_\odot$ (Kalberla et al. 2007). However, AGC 219533 is very dim in the optical; although an optical component is identified in initial ALFALFA matching, the M_{HI}/L_B ratio is roughly 5 and the star formation rate is $\sim$0.01 $M_\odot$/year. Recent estimates show that spirals such as the Milky Way have M_{HI}/L_B ratios <1 and produce several solar masses in stars each year (Haynes & Giovanelli

1984; Robitaille & Whitney 2010). The extremely suppressed star formation rate of AGC 219533 is likely due to it being a progenitor HI disk about to undergo a period of rapid star formation called a "starburst"; in order to verify this, the HI must exhibit an infall velocity structure (Leisman et al. 2017). If infall is not detected, then the object is likely obeying exotic star formation laws that are not yet understood (Leisman et al. 2017).

Both AGC 227982 and AGC 268363 are candidate dark galaxies, as ALFALFA failed to match the two sources to any optical counterpart. As such, they both exhibit star formation rates of zero. The HI mass-to-luminosity ratios for these sources are derived from the Sloan Digitized Sky Server (SDSS) optical magnitude limit: assuming the optical counterparts exist, but are too dim to be seen in SDSS, we derive a minimum M_{HI}/L_B ratio of 5 for AGC 227982 and 7 for AGC 268363. Because very few candidate dark galaxies have been documented in the literature (Cannon et al. 2015), it is unclear how the characteristics of these two sources relate to their optical darkness.

2. REDUCTION PROCESS OF VLA DATA

Due to its large beam size (3.5') in the L band feed array, Arecibo is unable to resolve these three small (40"−60") Almost Dark sources. Observations using smaller beams (higher resolutions) are thus necessary to examine the HI structure and kinematics of the sources. This study used data from the Very Large Array (VLA) to image these sources. The VLA, because it is an interferometer, is able to simulate a single dish telescope with a maximum baseline separation of 1 km in the D configuration and 3.6 km in the C configuration. The corresponding beam size is 40" in the D configuration and 15" in the C configuration. These resolutions optimize sensitivity to structure while still maintaining sensitivity to surface brightness.

AGC 219533 was observed for a total of 6 hours in the C configuration in the program VLA/14B-243, P.I. Leisman. Both AGC 227982 and AGC 268363 were observed for a total of 2 hours in the D configuration and a total of 6 hours in the C configuration, both in the program VLA/15B-170, P.I. Leisman.

The acquired data was then reduced and calibrated with the CASA software[1] at Macalester College. Radio frequency interference (RFI) in the visibilities was flagged by hand and calibrations were checked

---

[1] http://casa.nrao.edu

manually for errors. Each calibrated data set was removed of continuum sources and then cleaned, a process which transforms the visibilities into images. The clean parameters were optimized for each of the datasets in order to image at high resolutions while still maintaining sensitivity to surface brightness.

The resulting images are data cubes, three-dimensional models of the source that show the spatial distribution of HI in each channel. Cycling through the channels shows how the gas is structured and where it is brightest as a function of sky position and velocity. An example channel map of AGC 219533 may be seen in Figure 1. After the cubes were inspected and the detections confirmed, all the datasets for a given galaxy were imaged simultaneously.

In the single cubes, those channels containing the emission from the galaxy were selected and the noise (anything with a flux value of 2.5∗rms or less) masked out. The channels were then collapsed into two-dimensional images to show the gas across the entire velocity width of the galaxy. These images are called "moment maps." Moment 0 maps are proportional to the column density of HI gas as a function of position. From these maps, we derive the total flux, or power output, of the HI emission and examine the morphology of the source. Moment 1 maps show the recessional velocity of the gas as a function of position, and thus general rotation, of the gas. These two types of moment maps were produced for each source.

3. VLA DATA DISCUSSION

The moment 0 map, which shows HI mass surface density, effectively shows the power output of the gas as a function of position on the sky. By summing the power output over the total distribution of the gas, the total power (also called a flux integral, denoted by S_{HI}) is found. By taking into account the distance to the source, the intrinsic power can be found, which in turn depends on the quantity of HI present. As such, the HI mass of a source can be calculated from the following equation:

$$\frac{M_{HI}}{M\odot} = (2.36 \times 10^5) \left(\frac{D}{Mpc}\right)^2 (S_{HI}).$$

The mass estimates derived from the VLA data (see Table 2) are smaller than those estimated by ALFALFA (see Table 1) because the VLA flux integral values are also smaller. The decrease is due to the VLA's smaller beam and the non-zero spacing between the antennae. When taking observations with an interferometer

such as the VLA rather than a single-dish telescope such as Arecibo, sensitivity to surface brightness is exchanged for sensitivity to structure.

Moment 1 maps allow for the calculation of recessional velocities and total line width of the sources. Though HI emits photons at a specific wavelength, a rotating source will produce relatively blueshifted and redshifted photons, resulting in a width to the HI line. The wavelength around which the HI line is centered is also redshifted due to the expansion of space between the detector and the source. As such, calculating the difference between the highest and lowest velocity of HI gas gives the projection of the line width and rotational velocity of the source, and the recessional velocity corresponds with the center of that width. These are estimates, because the inclination of the disk is unknown.

Results from the analysis of the moment maps of each source can be seen in Table 2.

Taking into account that the VLA recovers less emission than Arecibo, the values derived from the VLA data are consistent with those derived by ALFALFA. The three galaxies are therefore real detections, and the moment maps produced for each are accurate and able to be analyzed qualitatively.

4. OPTICAL COMPARISON

Finalized moment maps for each galaxy were converted into contour maps using KVIS software[2], and then overlaid onto visible images in order to compare the HI components of the sources to the optical sky. The visible components for these galaxies were selected from the ground-based Sloan Digitized Sky Server (SDSS).

4.1. *AGC 219533*

The VLA moment maps confirm the association of a faint, blue optical counterpart to the HI. This is the same counterpart initially matched to the gas by ALFALFA. The optical counterpart, clearly seen in the bottom panel of Figure 2, occupies a much smaller angular area of the sky than the HI gas, which contributes to the galaxy's large M_{HI}/L_B ratio. The gas extends from the southwest (lower declination and higher right ascension) to the northeast (higher declination and lower right ascension). There is a diffuse,

---

[2] http://www.atnf.csiro.au/computing/software/karma/

extended feature in the northeast whose contours disconnect from those enclosing the majority of the HI gas.

The moment 1 map, seen in Figure 3, exhibits atypical velocity structure. Usually objects of comparable mass exhibit ordered rotation indicated by a gradient from high to low recessional velocity, but here there is a gradient from high velocity in the southwest, to low velocity in the center of the gas, to high again in the northeast. This structure is characteristic of outflow or infall, depending on the directionality, and suggests that AGC 219533 may be a progenitor about to undergo a starburst episode. Leisman et al. (2017), however, have been unable to identify an infall velocity structure when looking at the same VLA data.

To determine if the gas is experiencing outflow or infall, a moment 2 map may be produced, which shows the velocity dispersion of the gas. This would indicate how the gas is moving with respect to the rest of the gas nearby. Further, the inclination must be known. As of yet, neither of these exist for AGC 219533.

4.2. *AGC 227982*

The moment 0 map for this galaxy can be seen in the top panel of Figure 4. The source extends from west to east, and has some low brightness features that extend north (increasing in declination). The moment 1 map can be seen in the top panel of Figure 5. Discussion of the features there proceeds below.

Previously a candidate dark galaxy, AGC 227982 has been localized by the VLA beam at the coordinates (12:29:22.6, +04:21:48.6). This is offset from the initial ALFALFA coordinates of (12:29:22.5, +04:22:41.0) by roughly 1 arcminute in the declination direction. As seen in the bottom panel in Figure 4, the VLA coordinates coincide with a blue object just to the left of the red contour line. This blue object was identified in SDSS as a galaxy with a blue magnitude of -15.5. Due to the agreement between the position of the optical component and the densest component of the HI, this object is likely the optical stellar counterpart for AGC 227982. To confirm this, a recessional velocity is needed, because if the recessional velocity of the optical source matches that of the HI source, then the two must be the same object. However, the recessional velocity for the optical component is unknown, because SDSS has not derived a redshift for this object.

The optical source has been imaged by GALEX in the near-UV filter. It emits brightly in the NUV. This indicates the presence of intermediate- to high-mass main sequence stars, whose blackbody radiation peaks

at these wavelengths. Because these stars are short-lived compared to solar-type stars, they must be more recently formed, and so, from the GALEX images, it is likely that the stellar counterpart for AGC 227982 is actively forming stars.

As seen in Figure 4, the potential stellar counterpart is not very extended compared to the HI. Any extended structure is too dim for SDSS to detect. Further, the HI moment 1 map seen in Figure 5 exhibits a similar outflow/infall structure (high velocity at the ends and low velocity in the center of the source) to that seen in the moment 1 map of AGC 219533. This characterizes the stellar counterpart as similar to that of AGC 219533. AGC 227982 may be a progenitor galaxy on the cusp of a starburst episode as well.

4.3. *AGC 268363*

The moment 0 map of this galaxy can be seen in the top panel of Figure 6. The source has one dim feature that extends south (decreasing in declination). The moment 1 map of this source can be seen in the top panel of Figure 7. AGC 268363 exhibits a clearer gradient from high to low velocity, and thus much clearer rotation, than either AGC 219533 and AGC 227982. At low declination, the velocity does increase again in a steep gradient. Comparison to the moment 0 map in Figure 6 shows that this velocity increase corresponds to the dim, extended feature of the HI.

Previously a candidate dark galaxy, AGC 268363 was localized at position coordinates (16:07:11.2, +17:03:15.1), which are offset by roughly 1 arcminute from the ALFALFA coordinates (16:07:05.5, +17:03:15.0) in the right ascension direction. As seen in the bottom panel of Figure 6, the gas is now localized to a position which coincides with the position of an object cataloged in SDSS as a galaxy. This object is just to the upper right of the two foreground Milky Way stars in the optical image. It is visibly less blue in color than the optical component of AGC 227982, but this cannot be quantified as there are no magnitudes given in SDSS. Due to the lack of redshift data, it also cannot be determined if the two sources are in fact the same object. GALEX archive images of the optical source are unavailable. Due to the agreement in position between the optical and the HI, this stellar object is likely the optical counterpart for AGC 268363.

5. CONCLUSION

Moment maps and results from the analysis of three Almost Dark galaxies, AGC 219533, AGC 227982, and AGC 268363, have been successfully produced. These results come from high angular resolution imaging using the VLA interferometer. Due to the localization of the gas, all three galaxies are now associated with an optical stellar counterpart. AGC 219533 and AGC 227982 both exhibit either outflow or infall velocity structure, indicating that they may be progenitor starburst galaxies. More analysis of the kinematics of these two sources is necessary to characterize their velocity structures, which cannot be done without deriving the inclination of the sources.

AGC 227982 and AGC 268363 are no longer considered candidate dark galaxies due to their newly discovered optical counterparts. ALFALFA was unable to identify the optical counterparts because it was unable to localize the gas. As a result the ALFALFA coordinates were offset by roughly 1 arcminute in the declination for AGC 227982, and roughly 1 arcminute in the right ascension for AGC 268363. Offsets such as these are rare; the position coordinates found by ALFALFA are typically offset by a maximum of 20". However, an offset of roughly 1 arcminute is still within three standard deviations. These three galaxies' "dark" optical nature was due to instrumental error and not due to exotic, unusual physics. The discovery of their optical component shows that they are more consistent with current models of galactic evolution than previously thought. Future work should analyze these newly discovered optical components in order to fully characterize the galaxies.

Software: CASA, KVIS

REFERENCES

Cannon, J. M., Martinkus, C. P., Leisman, L., et al. 2015, AJ, 149, 72

Haynes, M. P., & Giovanelli, R. 1984, AJ, 89, 758

Haynes, M. P., Giovanelli, R., Martin, A. M., et al. 2011, AJ, 142, 170

Kalberla, P. M. W., Dedes, L., Kerp, J., & Haud, U. 2007, A&A, 469, 511

Leisman, L., Haynes, M. P., Janowiecki, S., et al. 2017, arXiv:1703.05293

Robitaille, T. P., & Whitney, B. A. 2010, Highlights of Astronomy, 15, 799

Galaxy	R.A.[a]	DEC.[a]	cz[b]	Width[c]	D[d]	Flux	$\log(M_{HI}/M_{\odot})$[e]	M_{HI}/L_B [f]	SFR[g]
			km/s	km/s	Mpc	Jy km/s			$M_{\odot}$/yr
AGC 219533	11:39:57.0	+16:43:17.0	6379	66	96	0.71	9.22	5	0.01
AGC 227982	12:29:22.5	+04:22:41.0	5010	34	73	0.38	8.69	>5	0
AGC 268363	16:07:05.5	+17:03:15.0	5284	33	79	0.50	8.87	>7	0

Table 1. ALFALFA data for each of the three sources. [a]: Right ascension and declination. [b]: Recessional velocity calculated from heliocentric redshift. [c]: Width of the HI emission line, which corresponds to the total rotational velocity of the source. [d]: Distance. [e]: Logarithm of the mass of the galaxy in units of solar masses. [f]: HI mass-to-luminosity ratio. [g]: Star formation rate.

Galaxy	R.A.	DEC.	cz	Width	Flux	$\log(M_{HI}/M_{\odot})$
			km/s	km/s	Jy km/s	
AGC 219533	11:39:57.0	+16:43:17.0	6379	68 ± 4	0.44	8.98
AGC 227982	12:29:22.6	+04:21:48.6	5010	55 ± 4	0.30	8.57
AGC 268363	16:07:11.2	+17:03:15.1	5284	40 ± 4	0.29	8.63

Table 2. VLA data for each of the three sources. Details about each column can be found in the caption of Table 1.
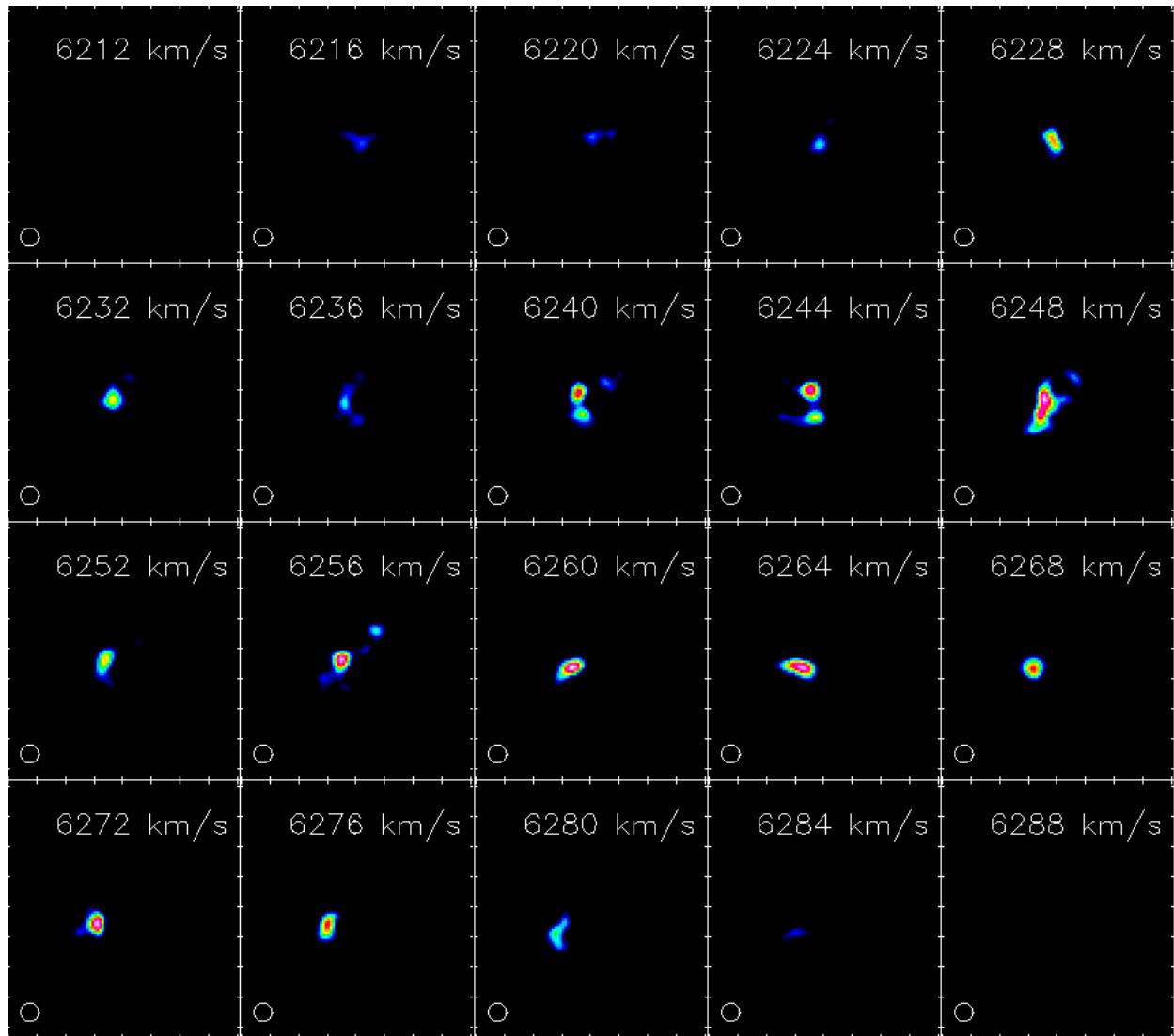
Figure 1. Channel map of AGC 219533. Starting at 6212 km/s in the upper left, each panel increases in velocity by 4 km/s and shows how the HI gas changes in structure and brightness as a function of position and velocity.
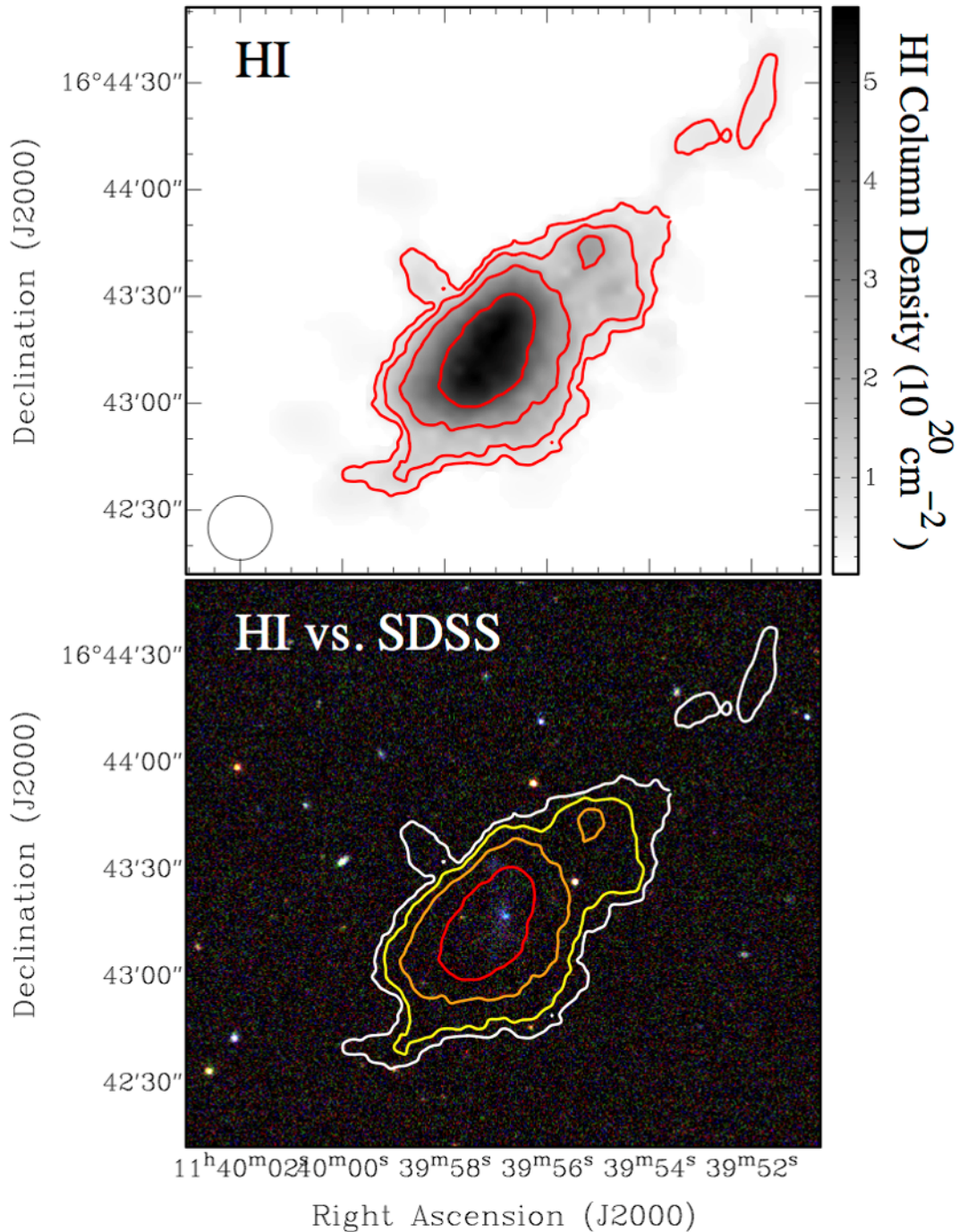
Figure 2. HI and SDSS imaging of AGC 219533. The fields are centered on the ALFALFA HI position centroid. The first panel shows the moment 0 map, the HI column density distribution; contours are shown at $(0.5,1,2,4) \times 10^{20}$ cm^{-2}. The second panel shows the same set of contours overlaid on a color SDSS mosaic. The VLA HI beam size is shown as a circle in the lower left corner of the moment 0 map. The optical counterpart is coincident with the ALFALFA HI centroid.
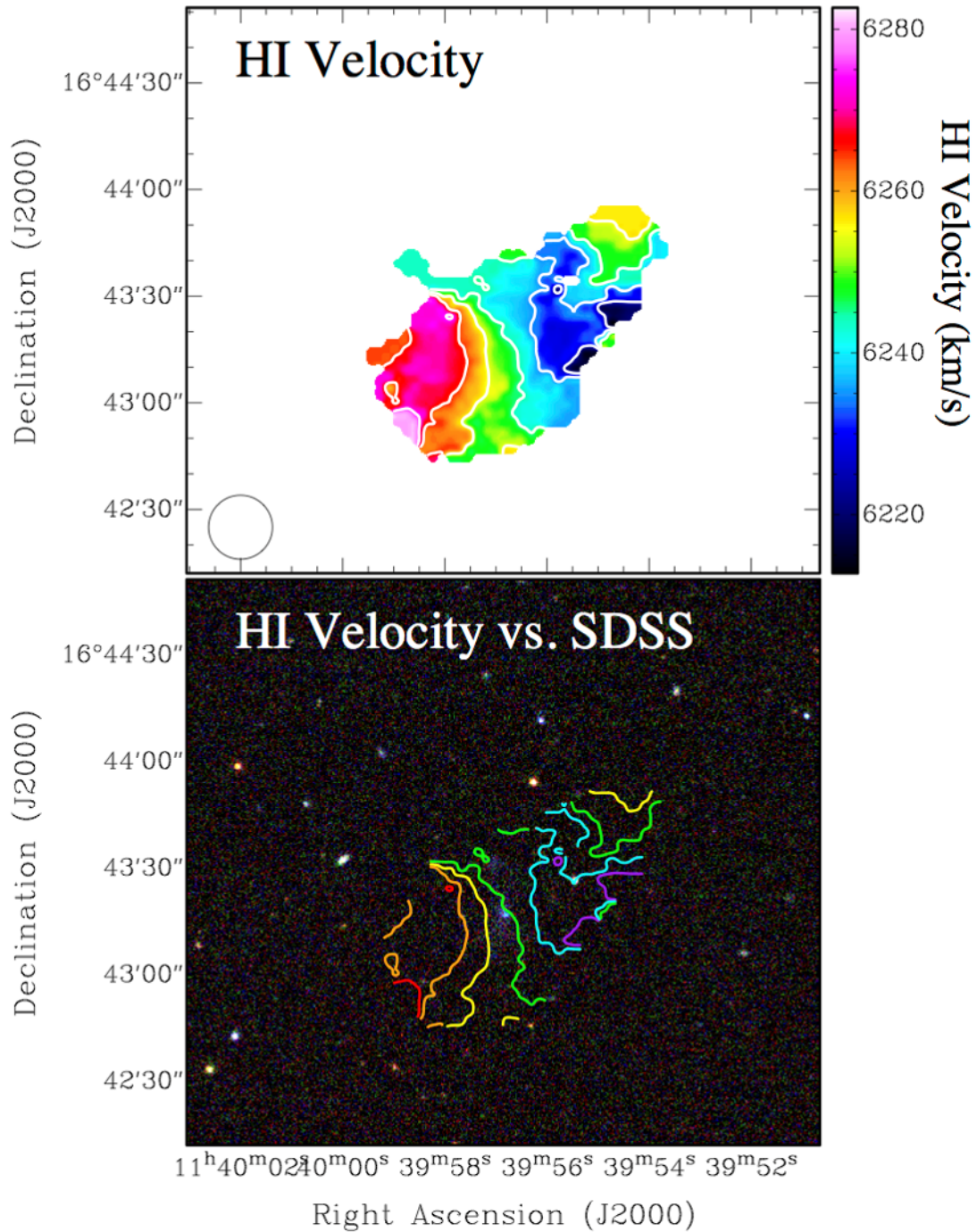
Figure 3. HI and SDSS imaging of AGC 219533. The fields are centered on the ALFALFA HI position centroid. The first panel shows the moment 1 map, the HI velocity field; contours are shown at (6225, 6235, 6245, 6255, 6265, 6275) km/s. The second panel shows the same set of contours overlaid on a color SDSS mosaic.
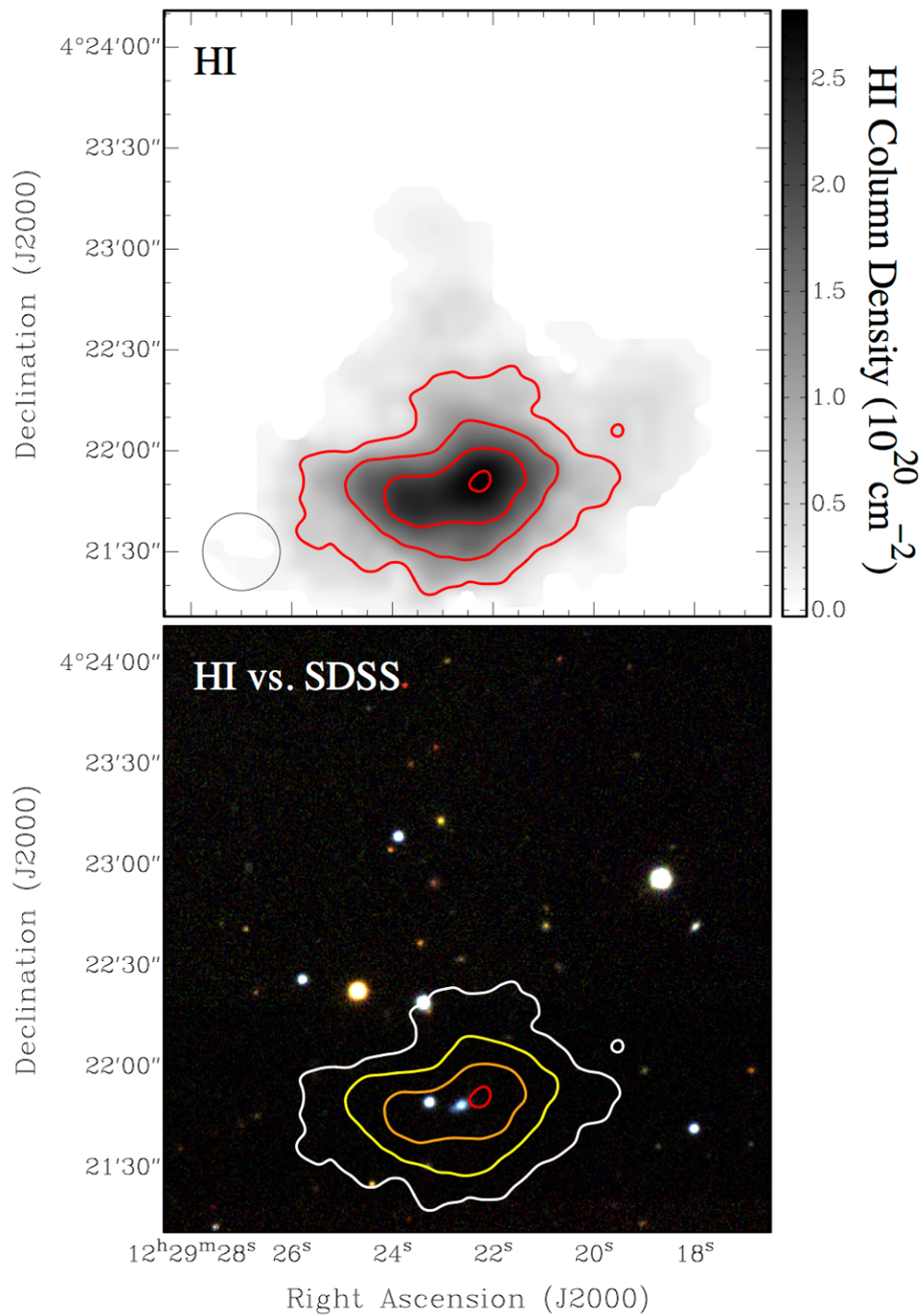
Figure 4. HI and SDSS imaging of AGC 227982. The fields are centered on the ALFALFA HI position centroid. The first panel shows the moment 0 map, the HI column density distribution; contours are shown at $(0.5, 1.25, 2.0, 2.75) \times 10^{20}$ cm^{-2}. The second panel shows the same set of contours overlaid on a color SDSS mosaic. The HI beam size is shown in the first panel. The optical counterpart is offset from the ALFALFA HI centroid by one arcminute in the declination direction.
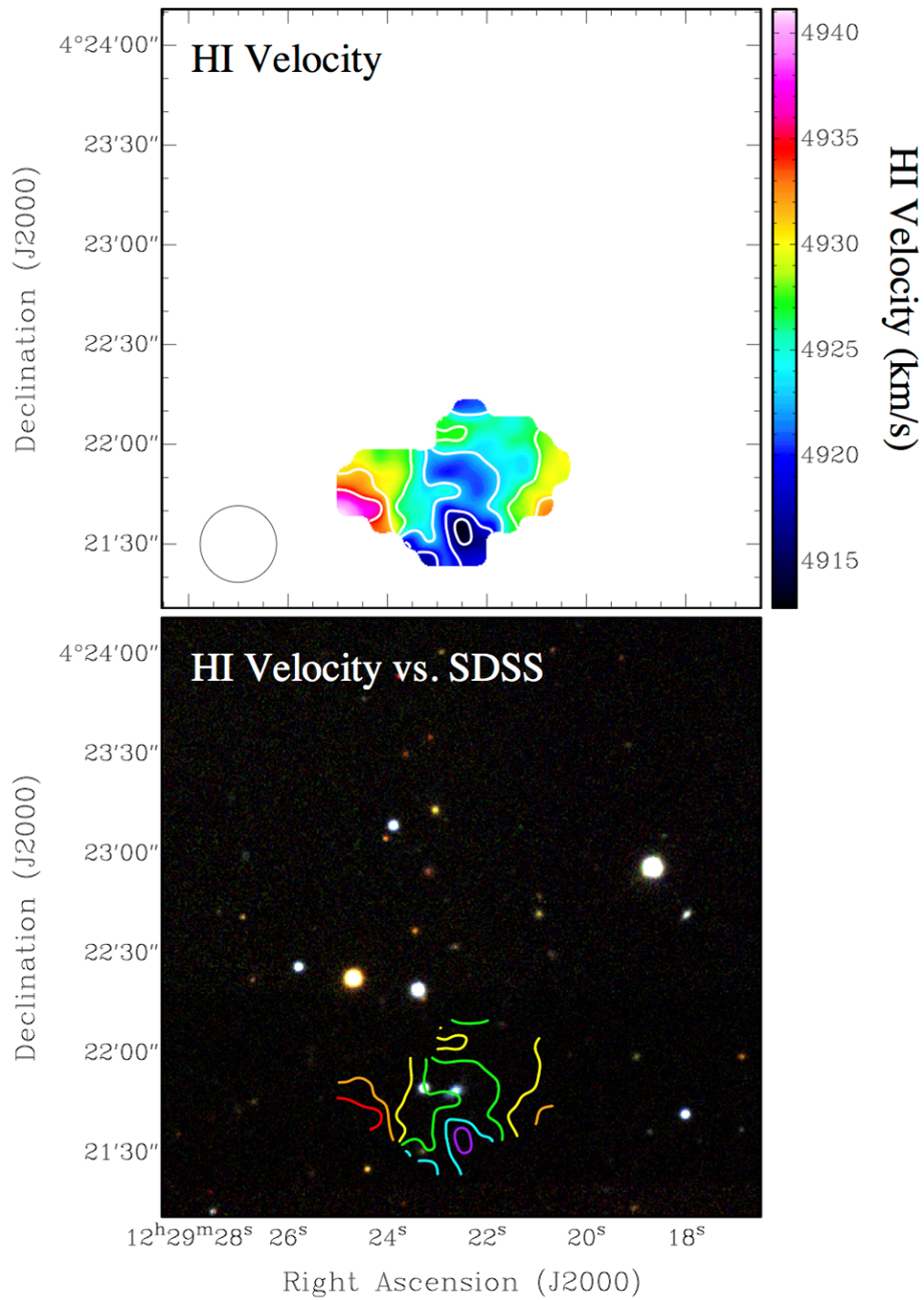
Figure 5. HI and SDSS imaging of AGC 227982. The fields are centered on the ALFALFA HI position centroid. The top panel shows the moment 1 map, the HI velocity field; contours are shown at (4915, 4919, 4923, 4927, 4931, 4935) km/s. The second panel shows the same set of contours overlaid on a color SDSS mosaic.
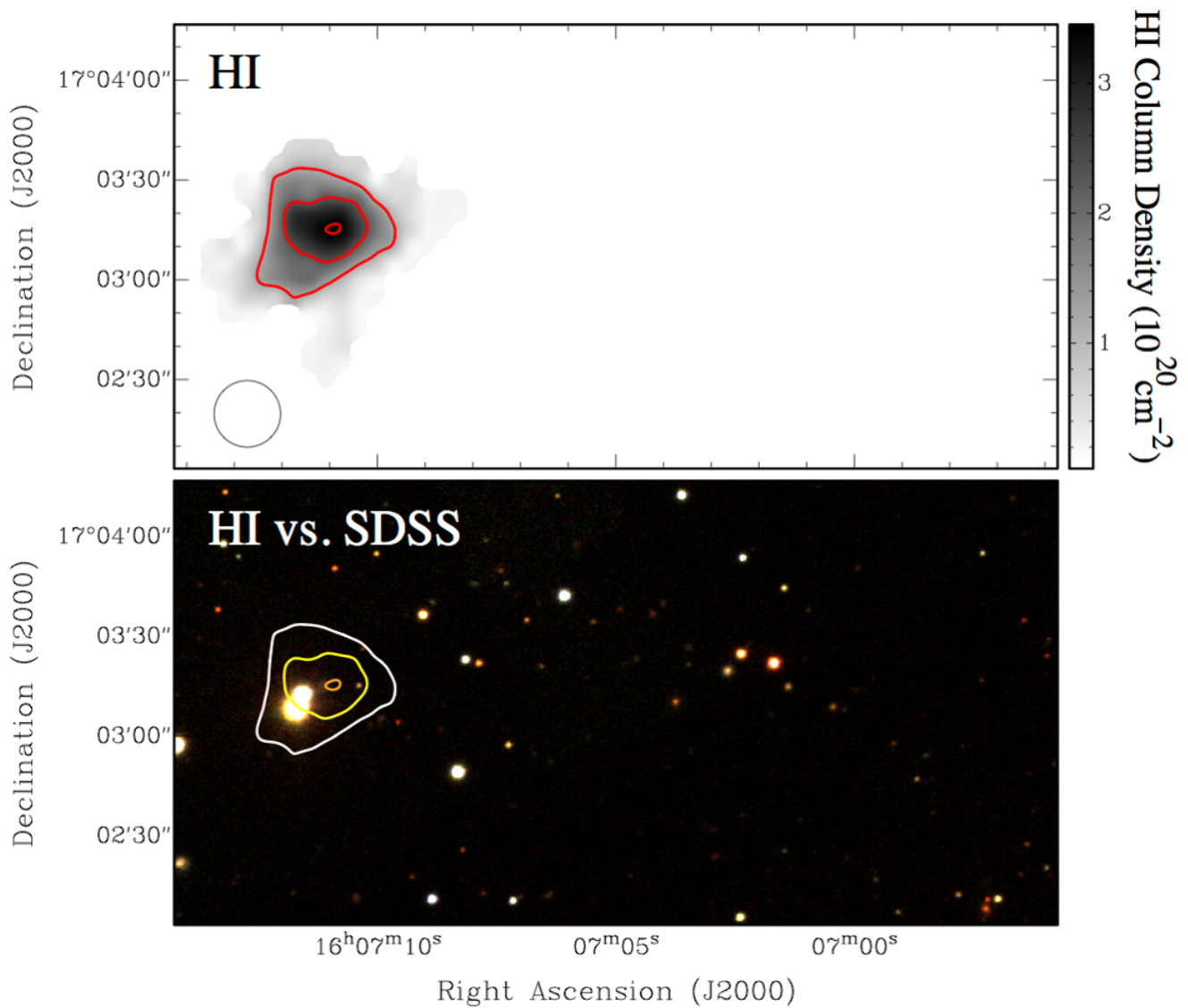
Figure 6. HI and SDSS imaging of AGC 268363. The fields are centered on the ALFALFA HI position centroid. The first panel shows the moment 0 map, the HI column density distribution; contours are shown at $(1.2, 2.3, 3.4) \times 10^{20}$ cm^{-2}. The second panel shows the same set of contours overlaid on a color SDSS mosaic. The HI beam size is shown in the first panel. The optical counterpart is offset from the ALFALFA HI centroid by one arcminute in the right ascension direction.
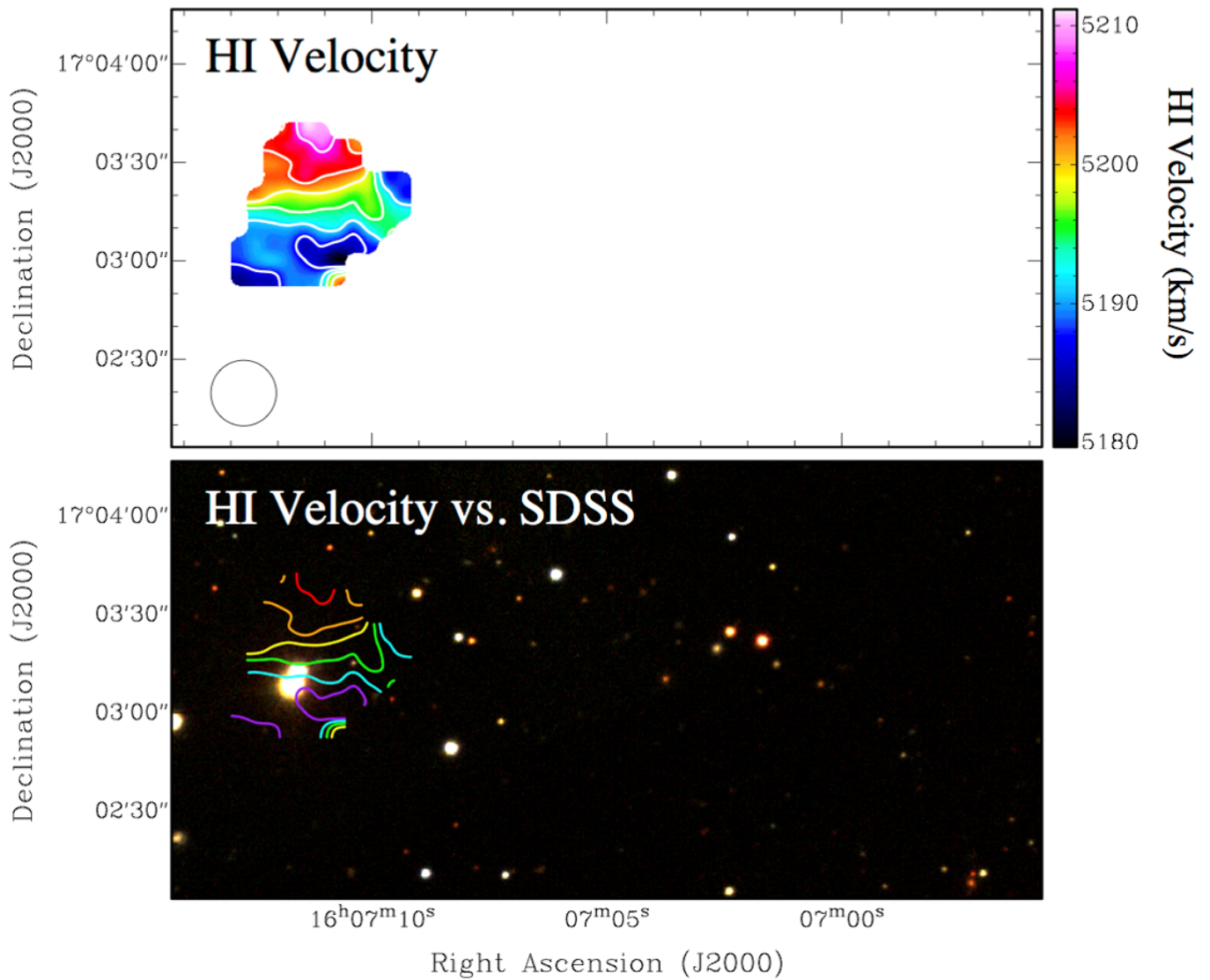
Figure 7. HI and SDSS imaging of AGC 268363. The fields are centered on the ALFALFA HI position centroid. The first panel shows the moment 1 map, the HI velocity field; contours are shown at (5187, 5191, 5195, 5199, 5203, 5207) km/s. The second panel shows the same set of contours overlaid on a color SDSS mosaic.