The Arecibo Galaxy Environment Survey XII : Optically dark HI clouds in the Leo I Group

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ABSTRACT

Using data from the Arecibo Galaxy Environment Survey, we report the discovery of five HI clouds in the Leo I group without detected optical counterparts. Three of the clouds are found midway between M96 and M95, one is only 10′ from the south-east side of the well-known Leo Ring, and the fifth is relatively isolated. HI masses range from $2.6\times10^6 - 9.0\times10^6 M_\odot$ and velocity widths (W50) from $16-42\,\mathrm{km\,s^{-1}}$. Although a tidal origin is the most obvious explanation, this formation mechanism faces several challenges. For the most isolated cloud, the difficulties are its distance from neighbouring galaxies and the lack of any signs of disturbance in the HI discs of those systems. Some of the clouds also appear to follow the baryonic Tully-Fisher relation between mass and velocity width for normal, stable galaxies which is not expected if they are tidal in origin. Three clouds are found between M96 and M95 which have no optical counterparts, but have otherwise similar properties and location to the optically detected galaxy LeG 13. While overall we favour a tidal debris scenario to explain the clouds, we cannot rule out a primordial origin. If the clouds were produced in the same event that gave rise to the Leo Ring, they may provide important constraints on any model attempting to explain

ИЗОЛИРОВАННЫЕ ОБЛАКА HI

Первый вариант.

- The leading hypothesis is that **the majority of those clouds are tidal debris produced during galaxy encounters,** with simulations supporting this (tidal or ram pressure stripping).

We also showed that our simulations readily produced isolated clouds of low velocity widths (< 50 km s−1) only,. Additionally, there are no indications of any more extended Hi features in their vicinity.

Второй вариант.

The clouds could be primordial ‘dark galaxies’ : rotating discs of gas embedded in dark matter halos. These have been proposed as a possible solution to the well-known ‘dwarf galaxy problem’.

НАБЛЮДЕНИЯ

- The Arecibo Galaxy Environment Survey **(AGES)** was a blind Hi survey performed at the Arecibo radio telescope from 2006-2019.
- При наблюдении Leo Ring (вокруг M96) были открыты несколько изолированных облаков HI
- All of the clouds are within 75 km/s of the velocity of M96..

DARK CLOUDS IN THE LEO I GROUP

Cloud 4 – есть отождествление с карликом. M_HI/M* = 1.4.

Table 1. Observed HI parameters for our selected clouds. All coordinates are J2000. Clouds are ordered in ascending declination.

Name	R.A.	Declination	Velocity	W50	W20	F_{tot}	MHI	S/N_{peak}	S/N_{tot}
			$km\,s^{-1}$	$km\,s^{-1}$	$km\,s^{-1}$	$Jy\,km\,s^{-1}$	$M_\odot$		
Cloud 1	10:44:47.79	11:27:34.05	960	38	100	0.188	5.5E6	12.3	17.0
Cloud 2	10:45:59.27	11:30:34.66	891	33	58	0.201	5.9E6	13.5	15.7
Cloud 3	10:45:36.17	11:44:20.90	894	42	73	0.275	8.0E6	13.6	19.0
Cloud 4	10:44:56.44	11:54:52.40	879	31	46	0.308	9.0E6	19.6	24.7
Cloud 5	10:50:25.91	12:09:54.62	916	16	27	0.088	2.6E6	9.2	8.2
Cloud 6	10:45:00.04	13:26:04.37	860	34	45	0.172	5.0E6	9.9	11.0

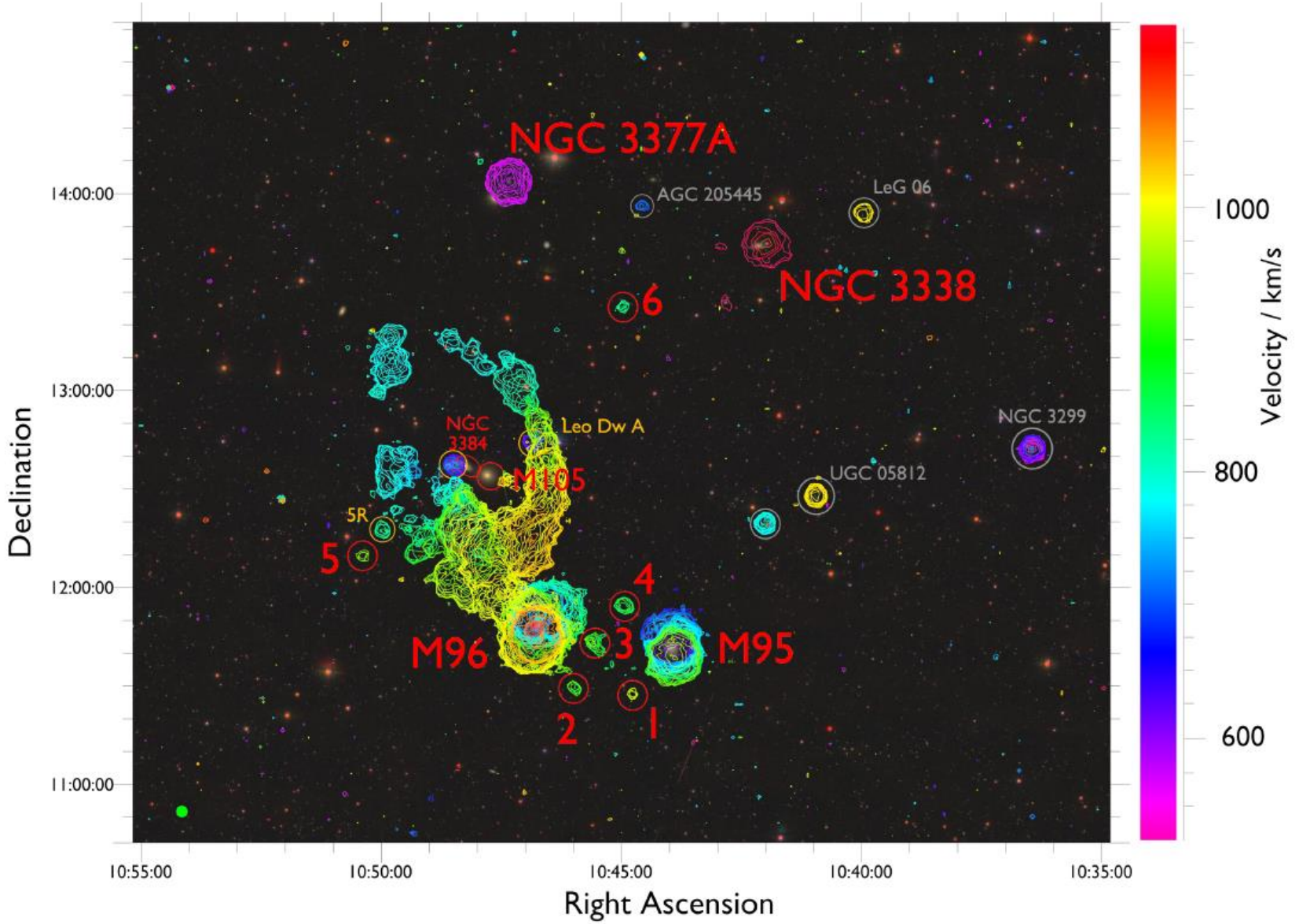
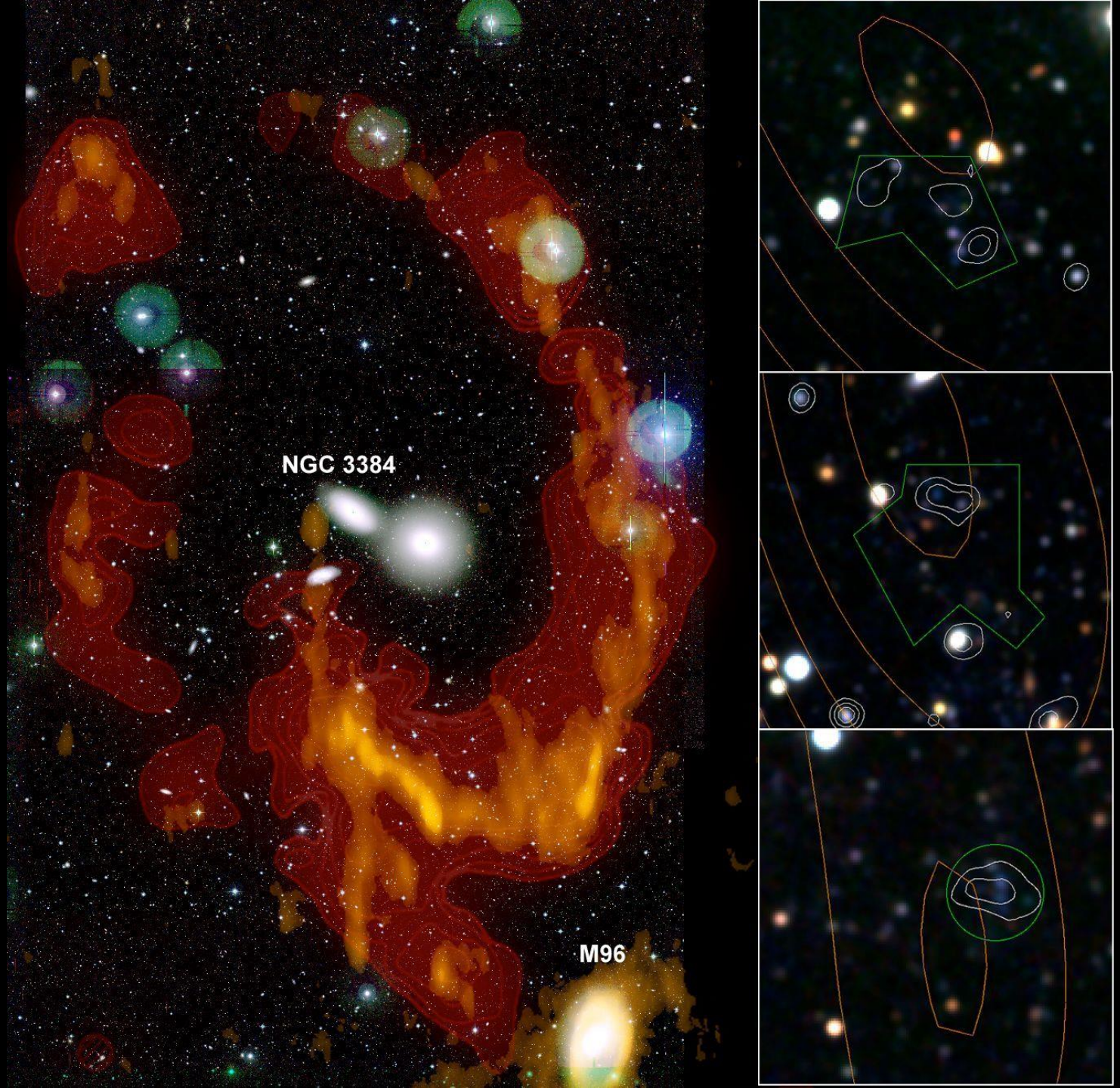


Figure 3. Renzogram of the whole survey region over the velocity range of the M96 subgroup. Each HI contour is at 3.5σ and coloured according to velocity, overlaid on an RGB image from the SDSS. The Arecibo beam size ($3.5'$, 11.3 kpc) is shown as a filled green circle in the lower left. HI clouds are numbered and selected major galaxies labelled in red. Other objects used for a few comparisons but not examined in detail are highlighted in orange, while other known objects not used in this study (here shown for the sake of completeness) are highlighted in grey.


NGC 3384
M96

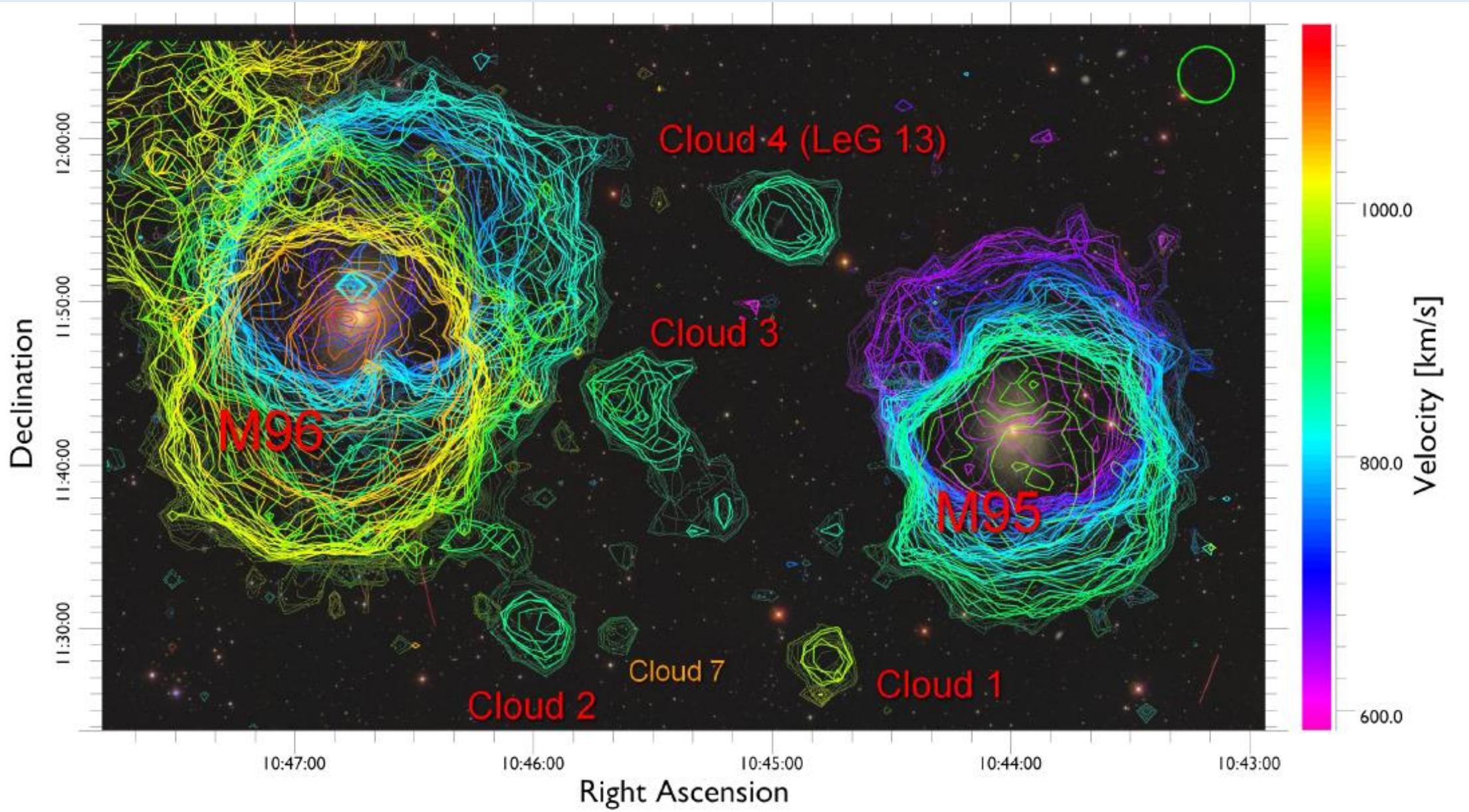


Figure 5. Renzogram of the M95-M96 region. The thick contours are from the standard AGES cube at 3.5σ. The thin contours are from a cube with additional Hanning smoothing (width 15) at 4σ. The green circle in the upper right shows the AGES beam. An additional feature tentatively identified as cloud 7 is also shown.

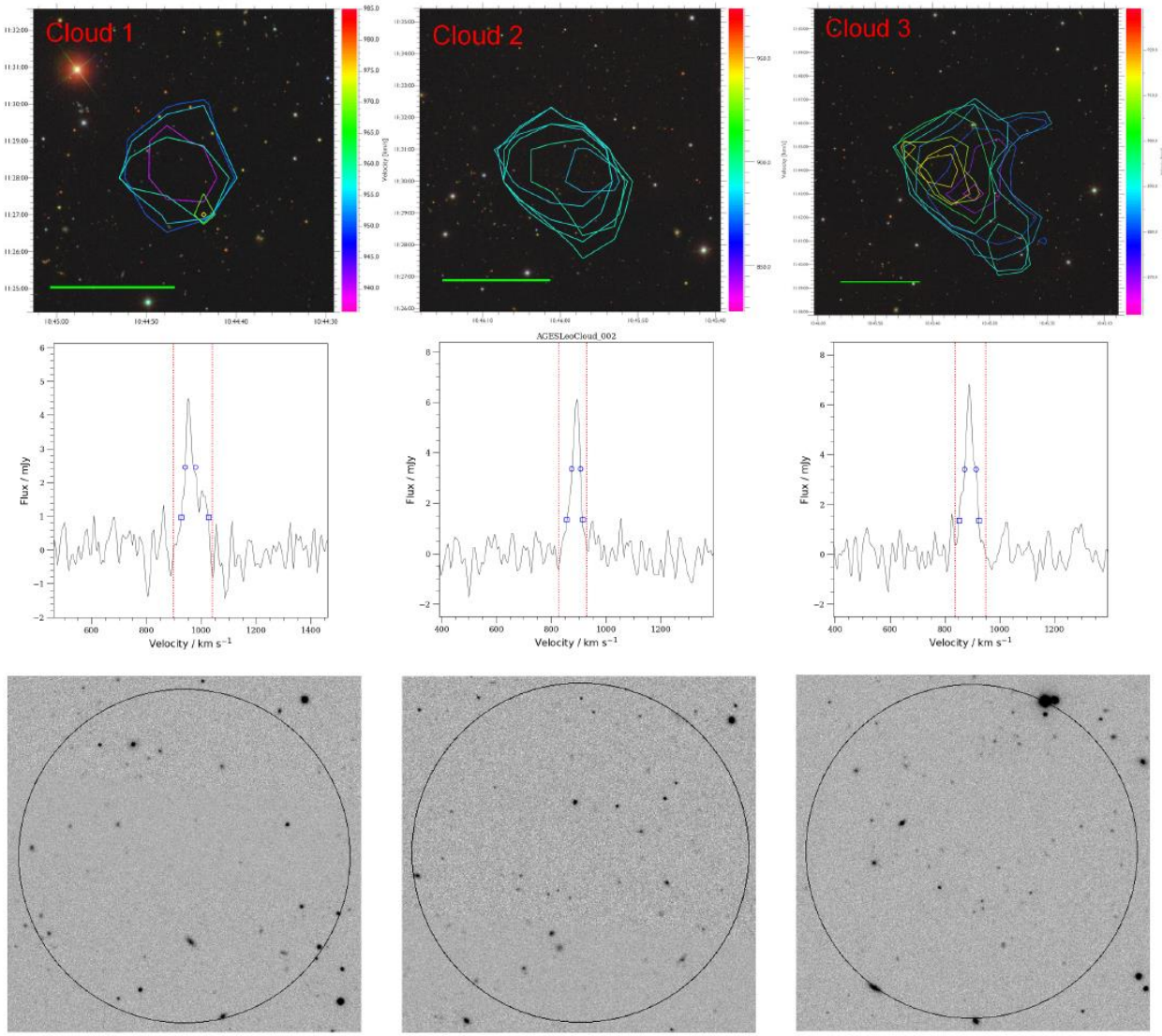


Figure 1. Clouds 1-3. The upper panel shows renzograms with the contour at 3.5σ and the Arecibo $3.5'$ beam (equivalent diameter 11.3 kpc) as a green line, overlaid on an a RGB image from the SDSS. The middle panel shows the spectra - red dashed lines show the profile window used for computing the HI parameters, blue circles show the positions of the W50 measurement and blue squares the W20 values. The lower panel shows the stacked g, r, i bands from the SDSS, with the black circle showing the Arecibo beam size, centred on the coordinates of the HI detections.

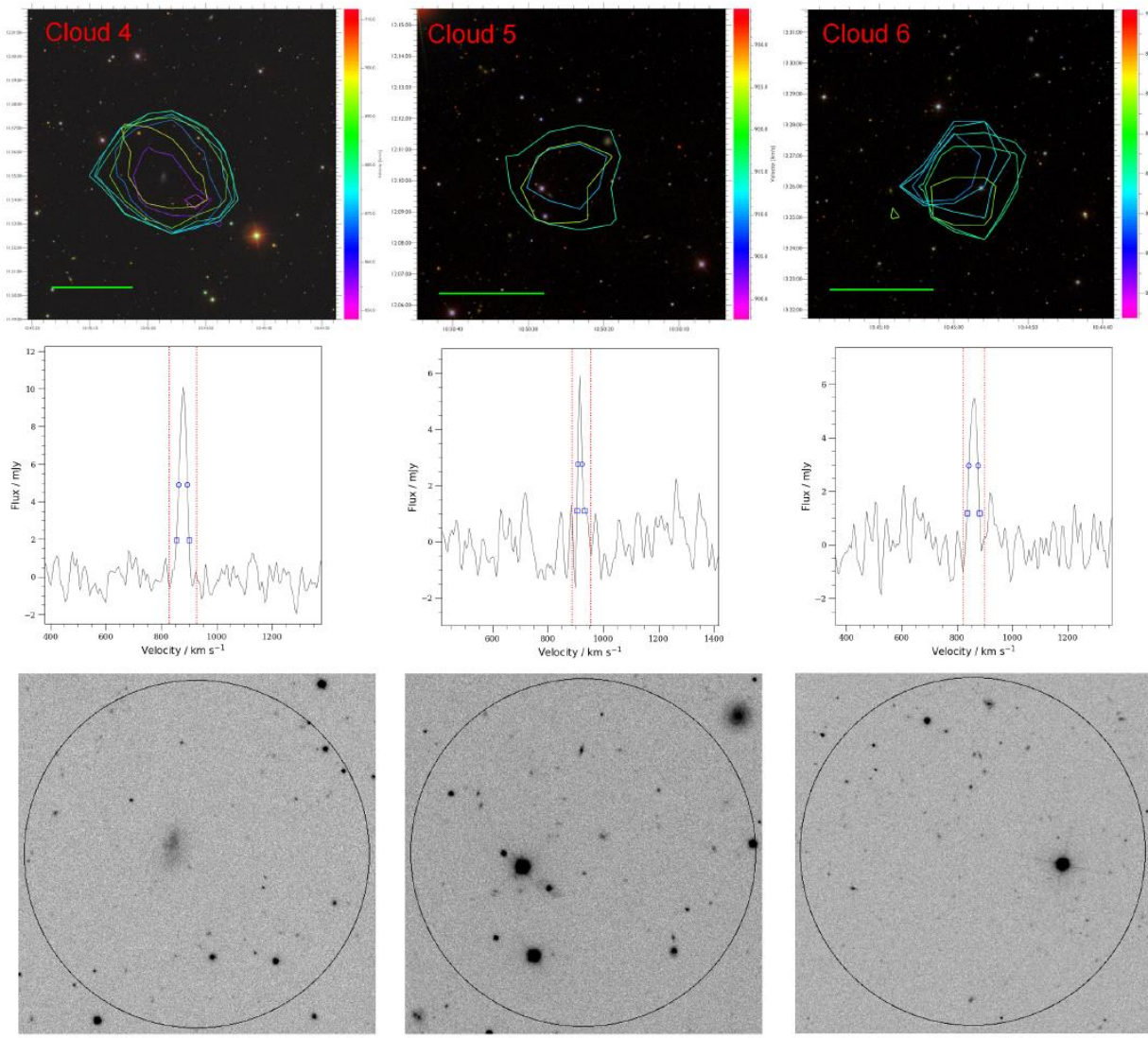
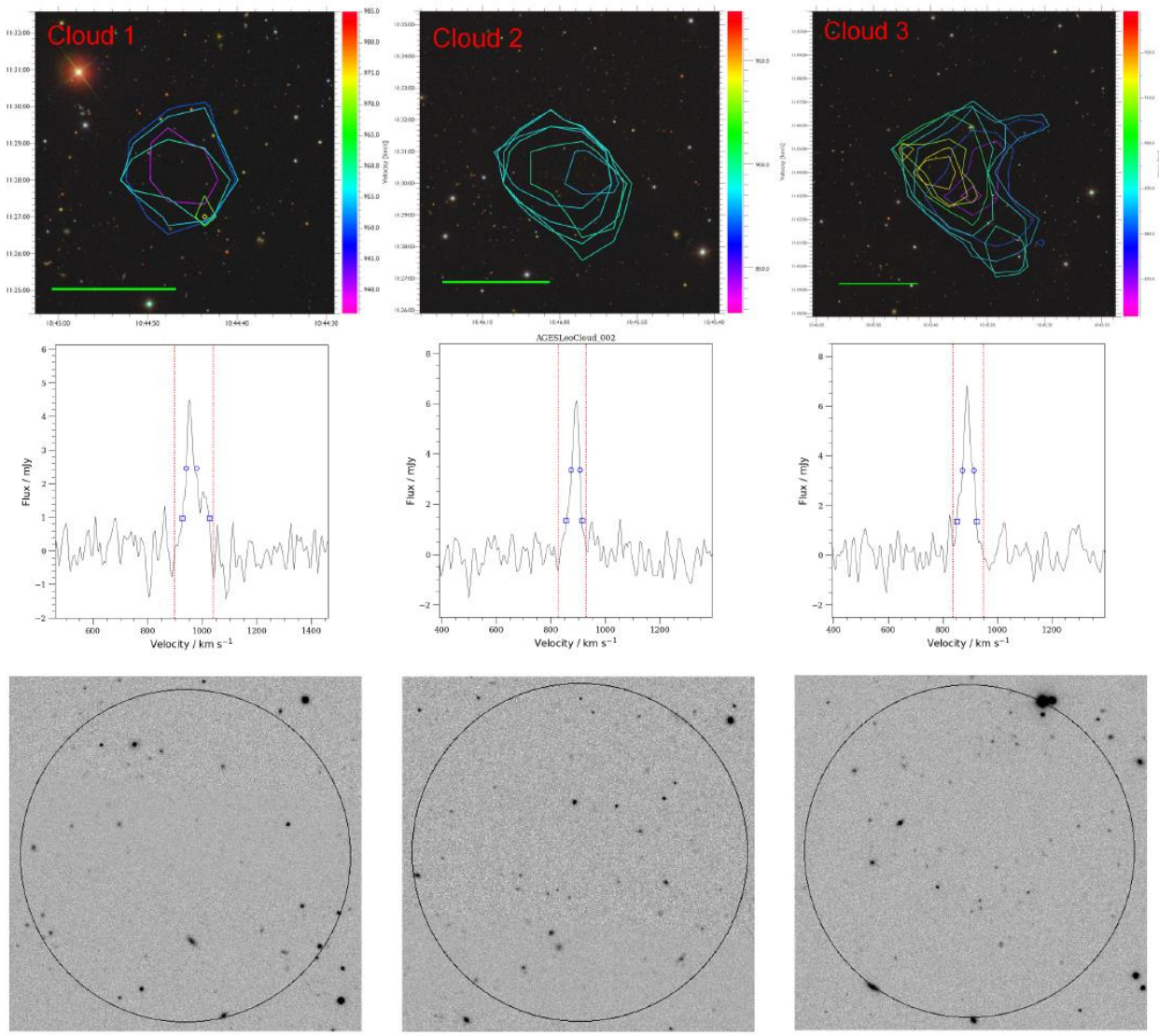


Figure 2. As for figure 1 but for clouds 4-6.



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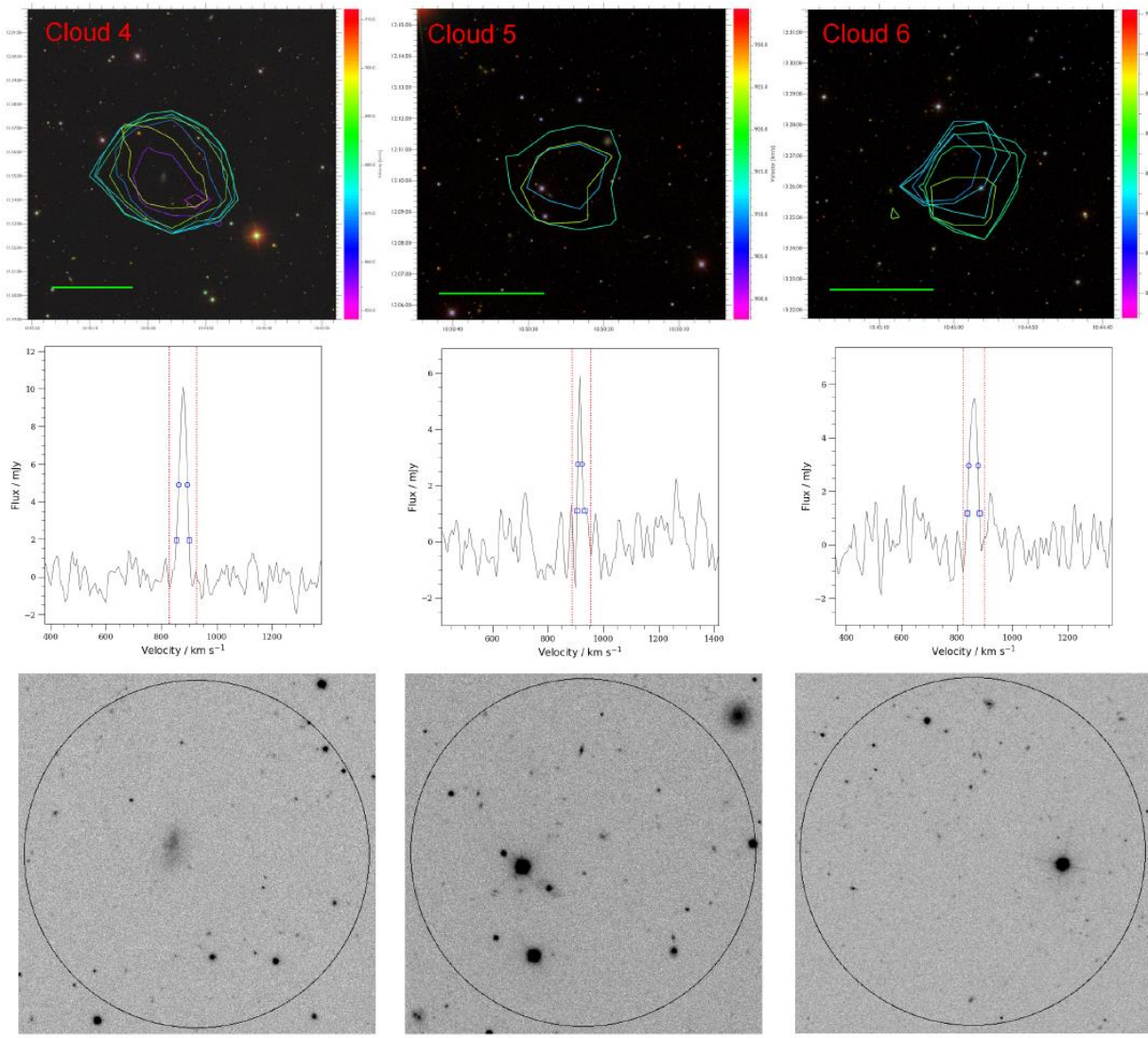

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Размер - только для Cloud 3 (~20 kpc).

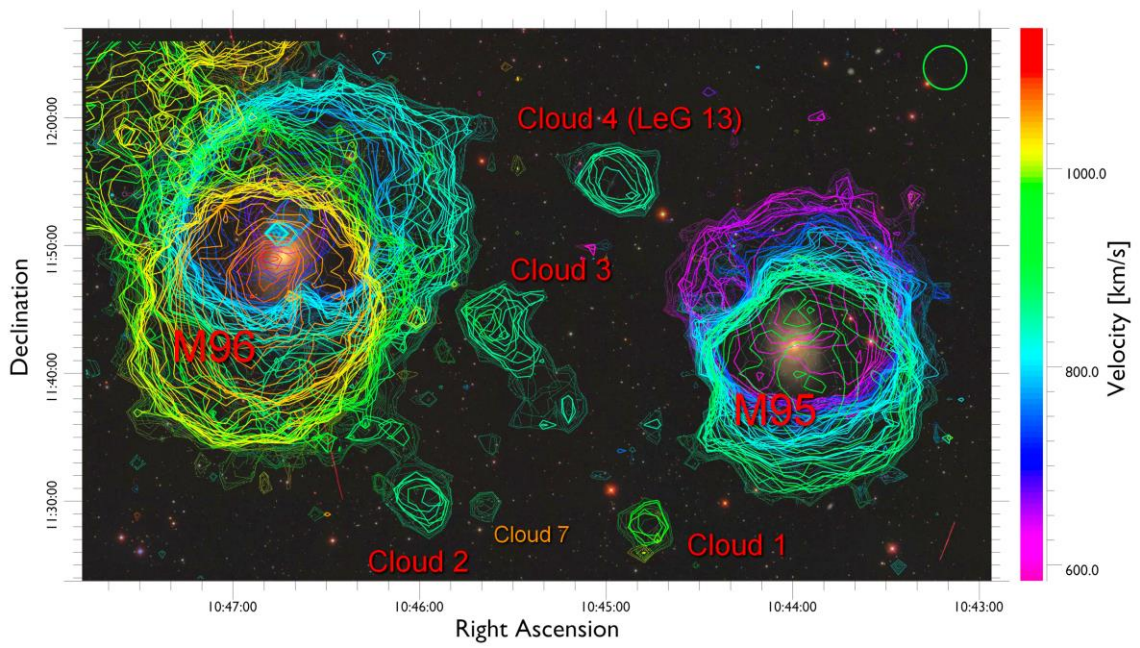
- There are two main possibilities for the nature of the clouds : transient tidal debris, and long-lived galaxies in which the Hi resides in a dark matter halo and the line width indicates rotation.
- The true size of most of the clouds is likely of the order of a few kpc, especially given the size of cloud 3;

Если нет DM, то гравитационно связанными облака быть не могут. Время расширения – несколько сотен млн лет. Debris?? Cloud 4 – a fading tidal dwarf ??

Но почему тогда не видно возмещения структуры в M95 и M96 в сторону clouds, , и нет хвоста или перемычки HI??

Если это галактики без звезд в поле DM, то их Mdyn $> 3\ 10^8$, Mdyn/M_HI >5.

- PV diagram (разрез вдоль прямого восхождения)



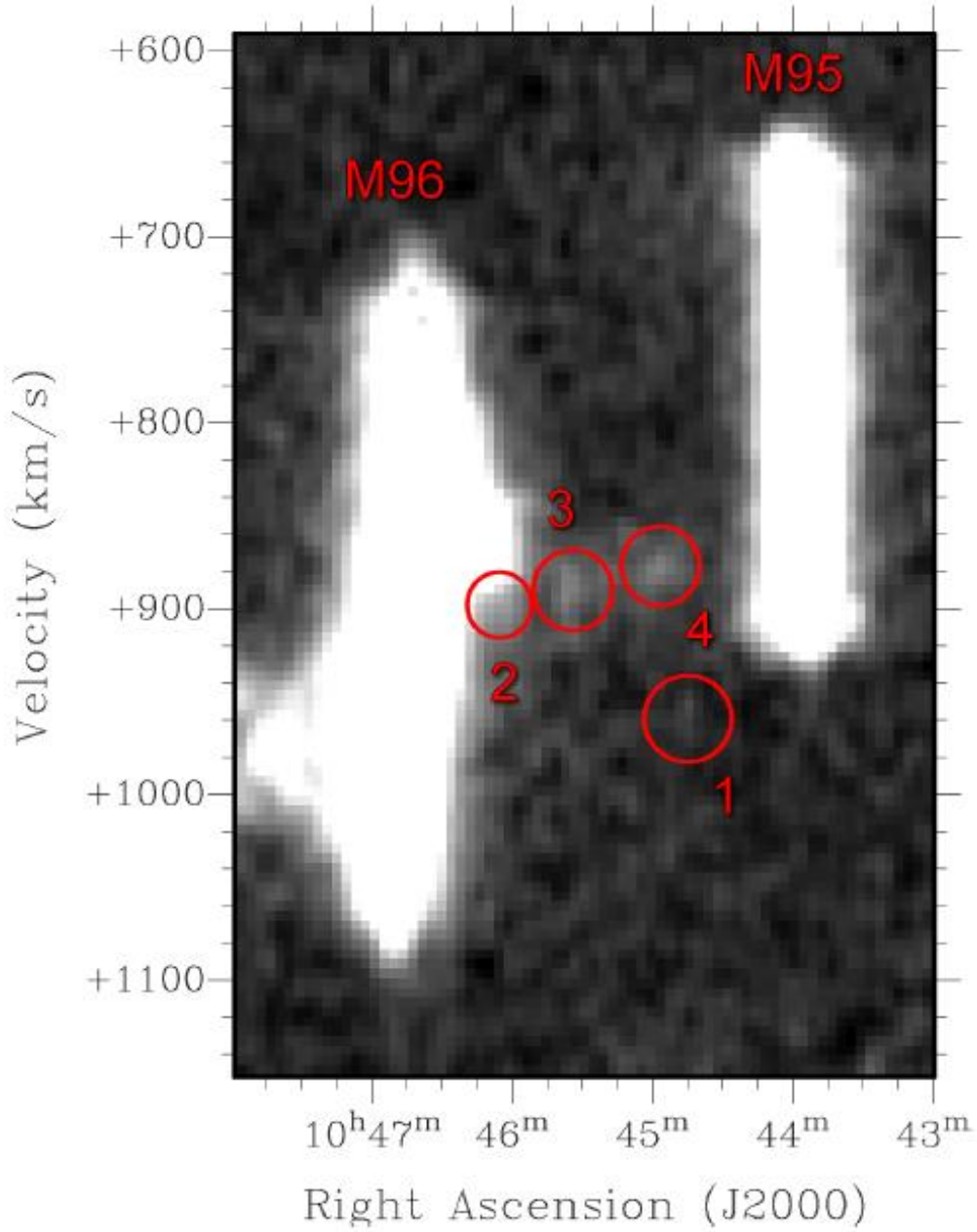
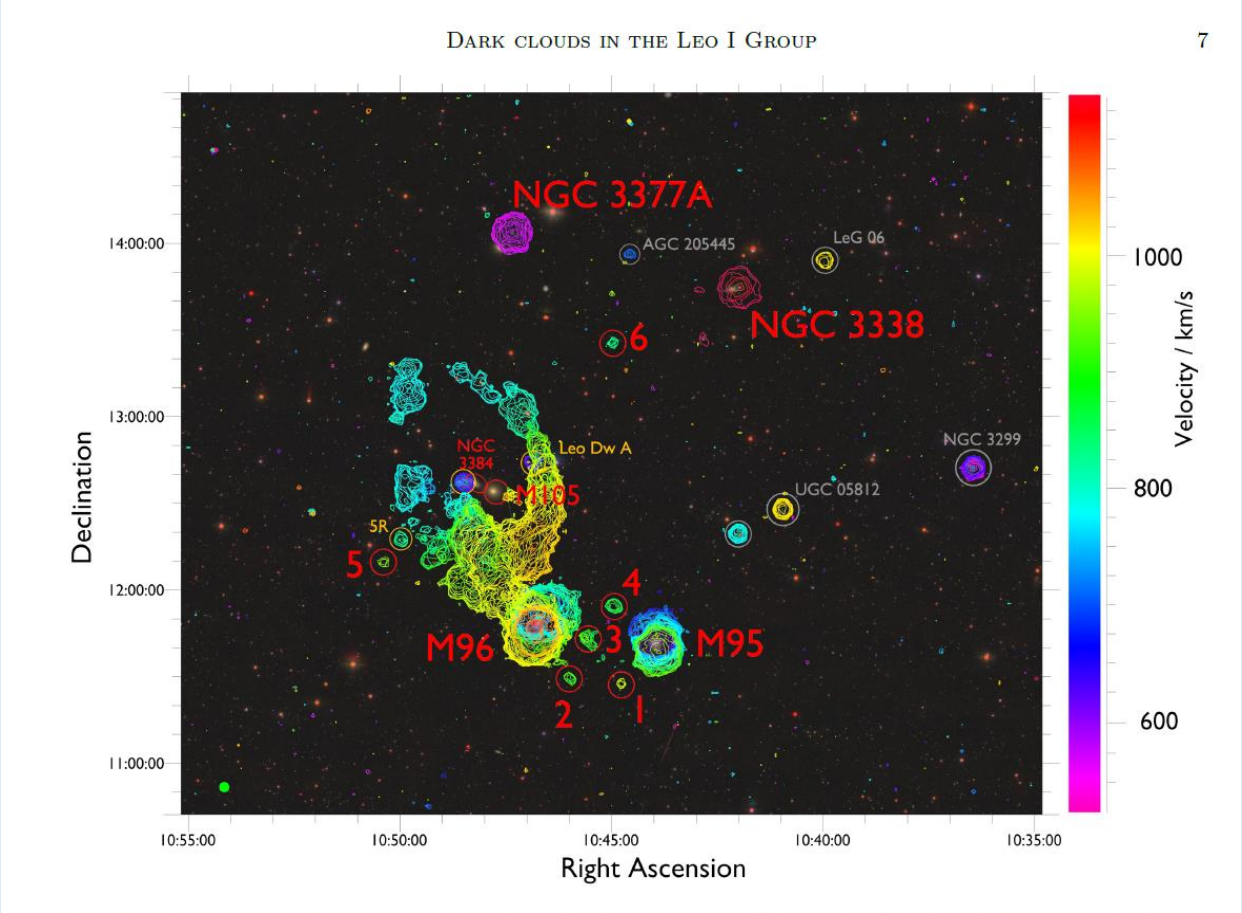


Figure 4. PV diagram of the M95-M96 region with a linear colour stretch, highlighting clouds 1-4.

- Cloud 5 – возможно принадлежит Leo Ring. Но $\Delta V > 150$ km/s.
- Cloud 6 - на >125 kpc от ближайшей точки Leo Ring. Есть 4 более близких галактики, но для них $\Delta V > 350$ km/s.
- The Hi masses of all four galaxies close to Cloud 6 range from two to four orders of magnitude greater than the clouds, implying that we should easily be able to detect any disturbance in the parent galaxy sufficient to account for the clouds.



- Синие кружки – VIRGO clouds.
- Overall, the main result appears robust : some clouds do

Deviate from the BTFR, but others do not. We note that there is a significant caveat in that the exact form of the BTFR whic depends strongly on the corrections used, especially for the stellar mass.

Paradoxically, it seems that some objects for which the evidence generally indicates a tidal origin (e.g. clouds 1 - 5 in Leo) actually lie on the standard BTFR

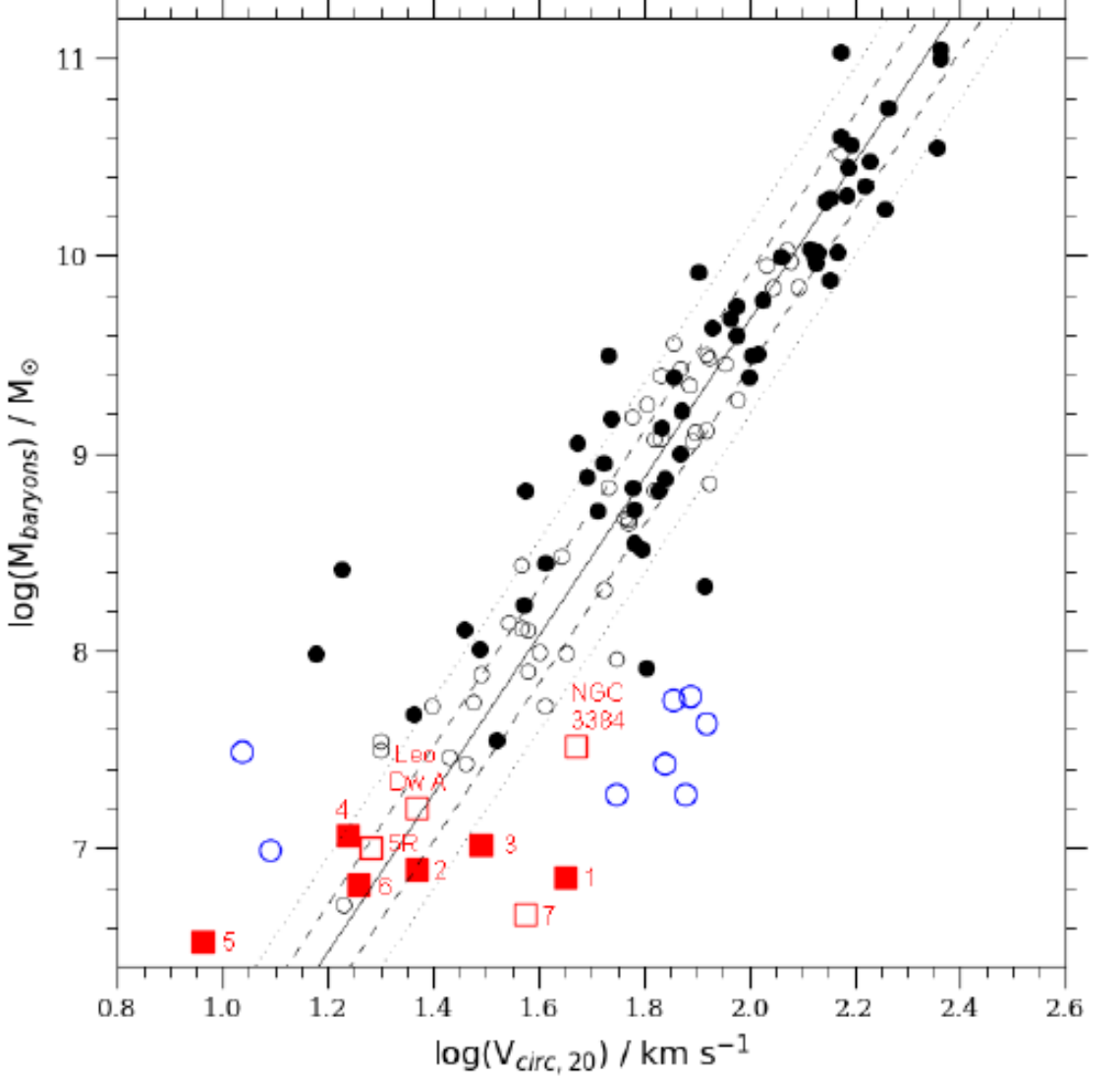


Figure 7. Baryonic Tully-Fisher relation using more sophisticated corrections for velocity width (derived for our sample from W20) and stellar mass, following the prescriptions of McGaugh (2012) and Springob et al. (2005) – for full details see the appendix. The colour scheme is as for figure 6, except that the open circles show the sample of McGaugh

The main difficulty for the tidal debris interpretation is the lack of any elongated tails found around any of the galaxies in this region.
A further oddity for the tidal debris scenario is that most clouds seem to obey the baryonic Tully-Fisher relation seen for normal, stable galaxies.

In short, the clouds are consistent with both tidal and galaxian interpretations and neither scenario can be denitively ruled out. We are currently examining a variety of formation scenarios for the Leo Ring using numerical simulations, which may eventually shed light on these smaller but intriguing clouds.