A-ph 1701.02750

The effect of ram pressure on the molecular gas of galaxies: three case studies in the Virgo cluster

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GA] 10 Jan 2017

Accepted to MNRAS

Ram pressure: влияние на H2.

- Противоречивые данные:

Most previous studies find that the molecular gas mass of the cluster population is not significantly different from that of field galaxies (Stark et al. 1986; Kenney&Young 1989). In addition, more recent studies are finding clumpy dust features in the upstream side of HI gas stripped galaxies, which are likely to be surviving dense clouds that are unveiled after diffuse atomic gas is removed (Crowl et al. 2005; et al).

However, the opposite results also have been reported. Rengarajan & Iyengar (1992) find that H2 mass normalized by the dynamical mass of galaxies tends to get larger with increasing clustercentric distance, which supports that molecular gas can be also deficient in the cluster environment. More recently, Fumagalli et al. (2009) have shown that the molecular gas surface density of galaxies that are HIdeficient tends to be low.

- Исследовались:

N4402, N4330, N4522

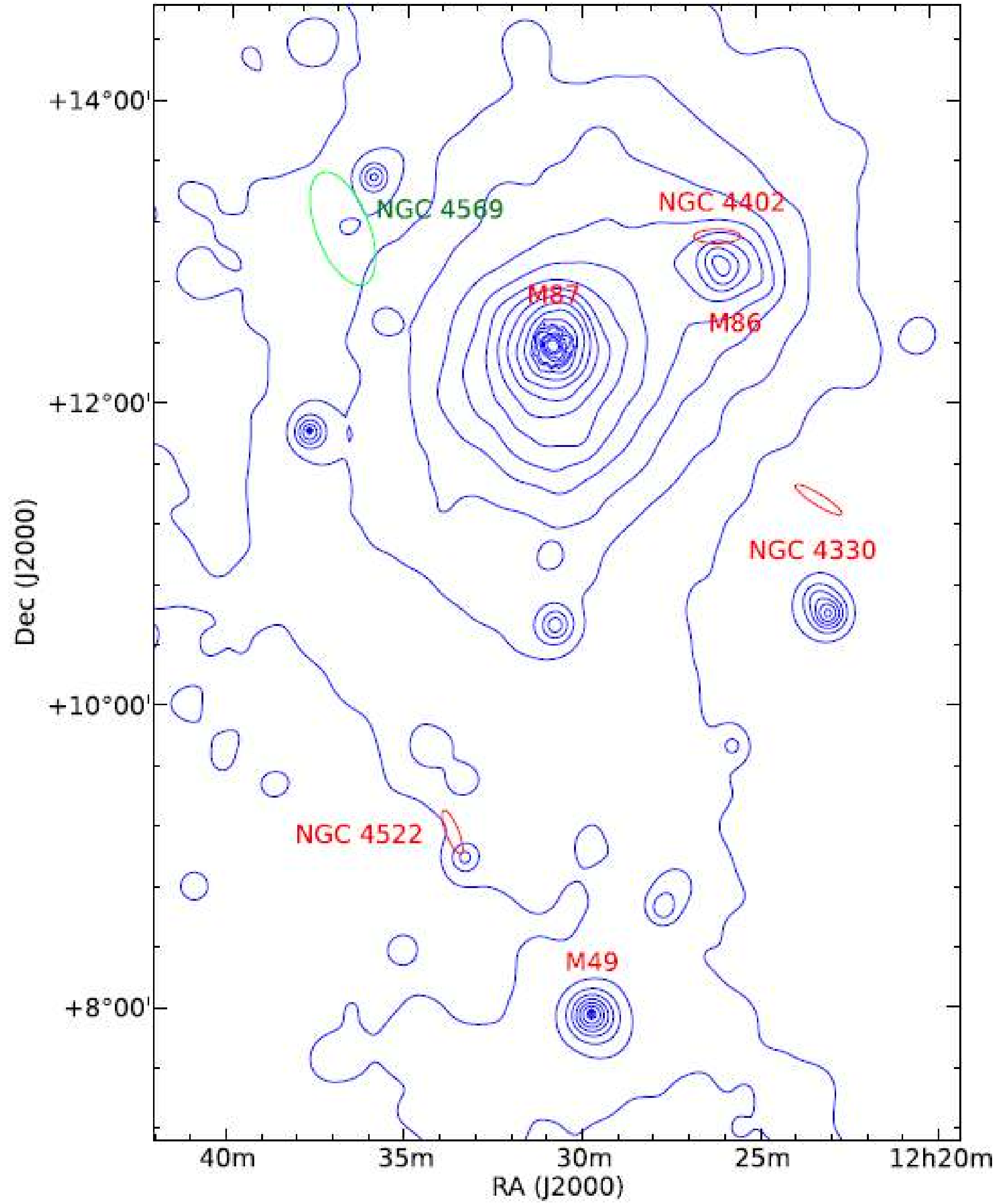


Figure 1. The locations of our sample are shown on the *ROSAT* X-ray map (blue contours: Böhringer et al. 1994). Red ellipses represent the position

Table 1. General Information of Sample Galaxies[a].

Galaxy	NGC 4330	NGC 4402	NGC 4522
Right ascension (J2000)	$12^h23^m17^s.0$	$12^h26^m07^s.6$	$12^h33^m39^s.7$
Declination (J2000)	$+11°22'03''.5$	$+13°06'47''.4$	$+09°10'30''.2$
Morphological type	Sc	Sb	SBc
Inclination (°)	79	82	79
Position angle (°)	60	89	35
V_{rad} (km s^{-1})[b]	1565	232	2328
D_{25} (arcmin)	2.29	3.55	3.47
Total apparent *B*-band magnitude	12.02	12.05	11.86
Total *K*-band luminosity (10^9 $L_{\odot,K}$)[c]	6.58	21.30	5.64
M_{HI} ($10^8 M_\odot$)[d]	4.45	3.70	3.40
def_{HI}[d,e]	0.80	0.74	0.86
d_{M87} (°)[d]	2.1	1.4	3.3

[a]General information of the sample galaxies from Paturel et al. (2003) (HyperLeda, http://leda.univ-lyon1.fr/).

[e]$def_{HI} = \langle \log \overline{\Sigma}_{HI,all} \rangle - \log \overline{\Sigma}_{HI,obs}$, where $\langle \log \overline{\Sigma}_{HI,all} \rangle$ is the mean HI surface density of field galaxies (Haynes & Giovanelli 1984), and $\log \overline{\Sigma}_{HI,obs}$ is the mean HI surface

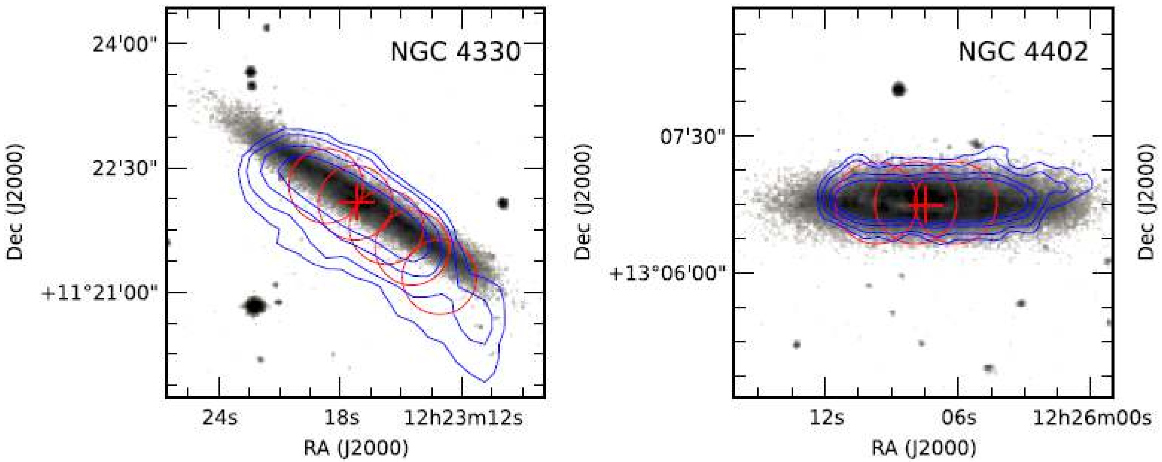


Figure 2. The HI distribution of NGC 4330, NGC 4402 and NGC 4522 (from left to right) is shown in blue contours overlaid on the Digitized Sky Survey 2 (DSS2, https://archive.stsci.edu/dss/index.html) red image. The red cross indicates the stellar disc centre of each galaxy estimated from *Spitzer* 3.6 μm data (Salo et al. 2015), and the thin red circles represent the SMA observation points, each of which corresponds to the size of the primary beam at 230 GHz ($\approx$54 arcsec).

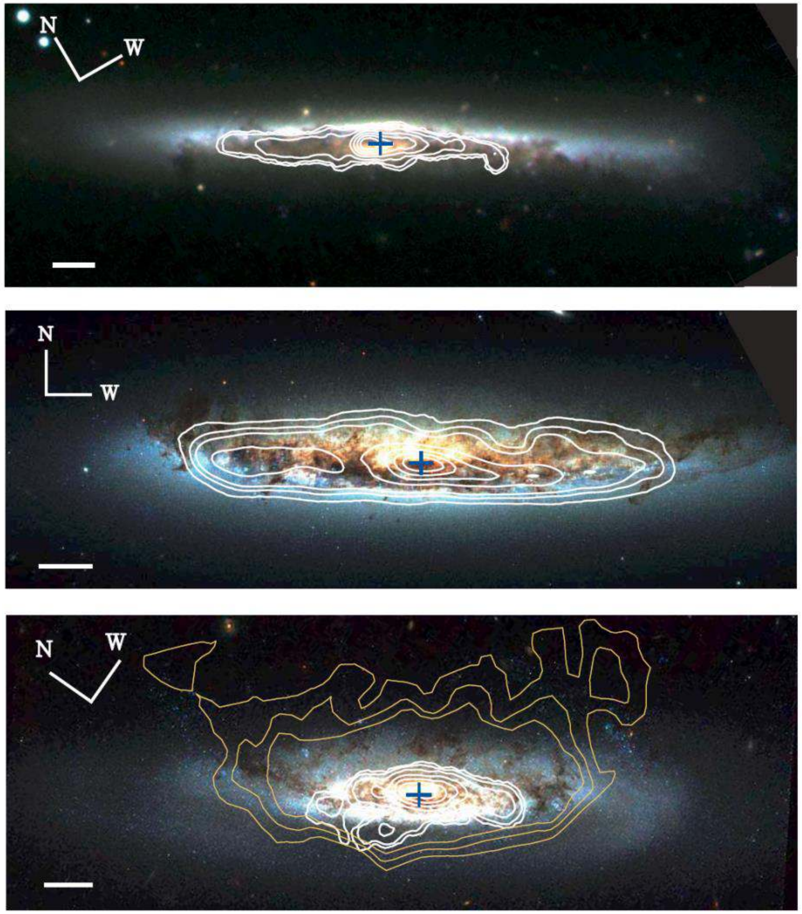
- CO morphology in our sample is all found to be highly asymmetric and disturbed.

12CO (2-1) contours
(white conours: SMA,
yellow contours: IRAM)

Table 3. SMA CO properties of sample galaxies.

	NGC 4330	NGC 4402	NGC 4522
W_{20} (km s^{-1})	208	255	176
W_{50} (km s^{-1})	184	226	159
V_{sys} (km s^{-1})	1562	246	2326
S_{CO} (Jy km s^{-1})	182.22 ± 8.02	1400.76 ± 11.91	139.43 ± 4.77
M_{H_2} (10^8 $M_\odot$)[a]	1.19 ± 0.05	8.83 ± 0.08	0.88 ± 0.03

Note. [a]The CO-to-H_2 conversion factor of 3.2 $M_\odot$ pc^{-2} (K km s^{-1})$^{-1}$ is adopted from Strong & Mattox (1996).



1. 12CO (2−1) contours (white conours: SMA, yellow contours: IRAM) are overlaid on optical colour images (NGC 4330: WIYN 3.5m telescope ur image; Abramson et al. 2011, NGC 4402 and NGC 4522: *HST*[3] BVI colour images). Top: NGC 4330. Middle: NGC 4402. Bottom: NGC 4522. ...cal scale bar (20 arcsec) of each galaxy is shown at the bottom left. The blue cross indicates the stellar disc centre of each galaxy.

NGC4402

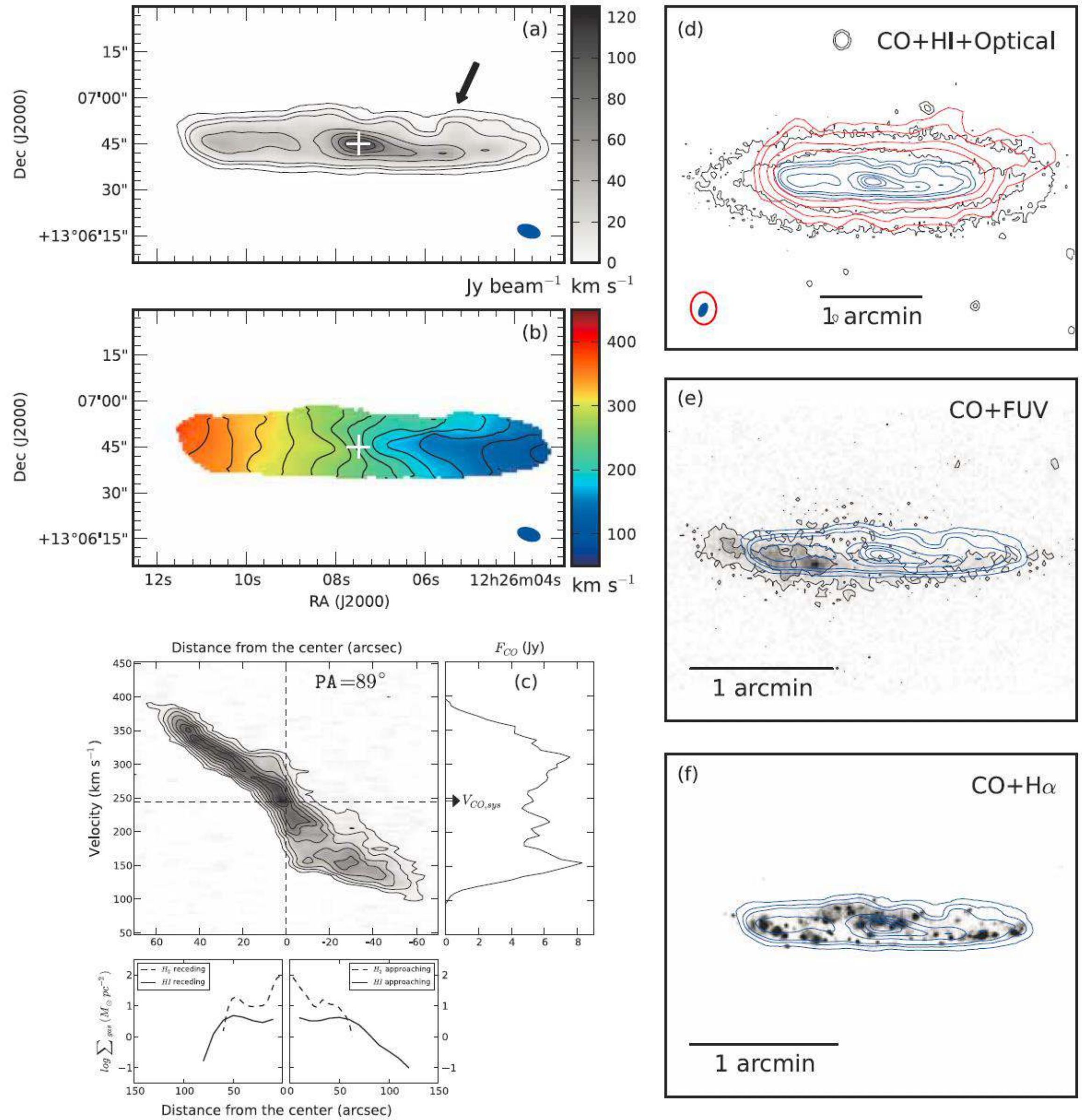
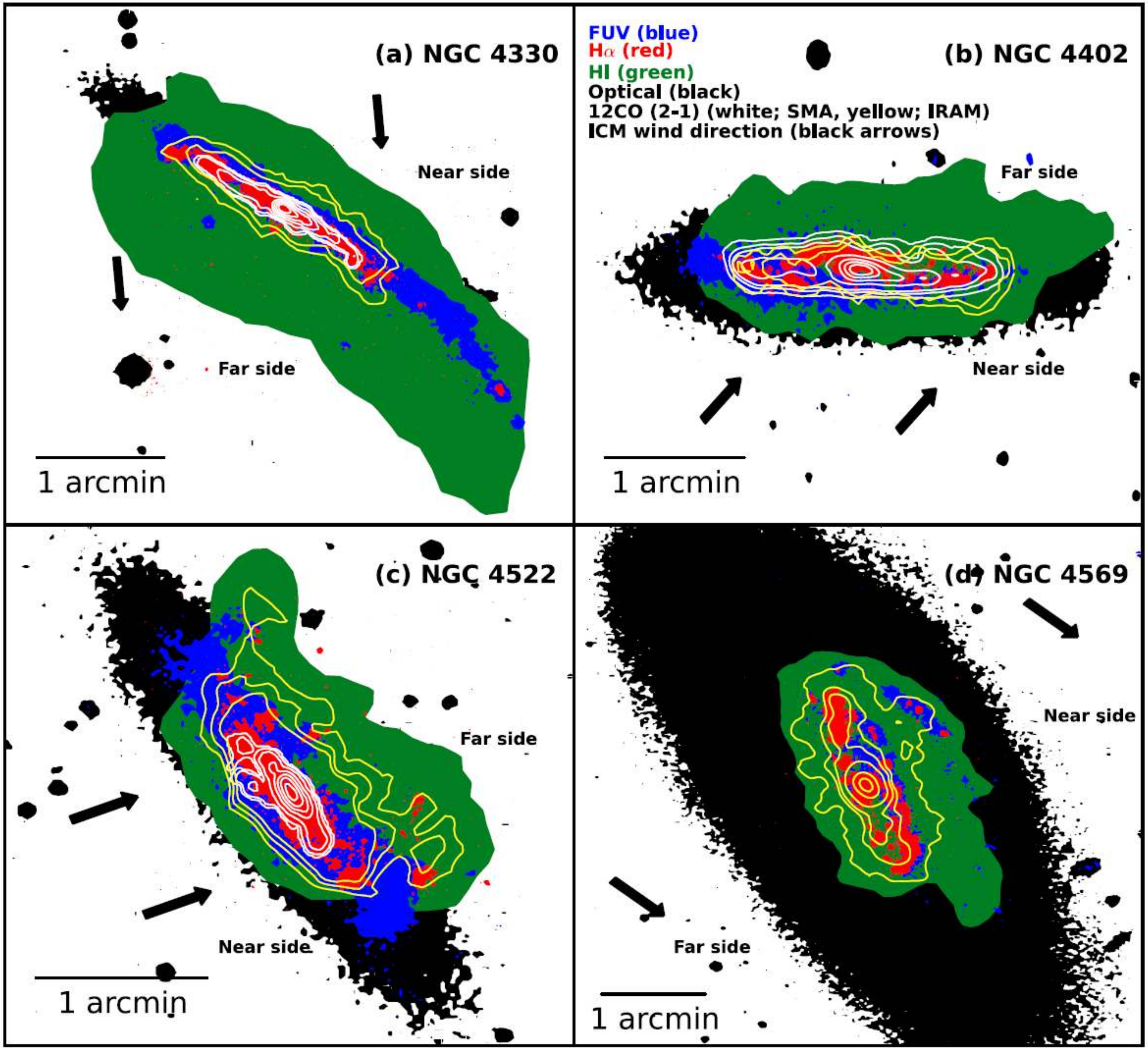


Figure 4. NGC 4402: (a) 12CO (2−1) integrated intensity map (the 0th moment) in grey-scale with contours. Contour levels are 1, 5, 10, 30, 50, 70, 90 Jy beam^{-1} km s^{-1}. The synthesized beam size is 7.21 arcsec × 3.89 arcsec (blue ellipse at the bottom right). The white cross indicates the stellar disc centre.



(a) NGC 4330
Near side
Far side
1 arcmin
FUV (blue)
Hα (red)
HI (green)
Optical (black)
12CO (2-1) (white; SMA, yellow; IRAM)
ICM wind direction (black arrows)
(b) NGC 4402
Far side
Near side
1 arcmin
(c) NGC 4522
Far side
Near side
1 arcmin
(d) NGC 4569
Near side
Far side
1 arcmin

The CO kinematics suggests that the ICM pressure can disturb the molecular gas, deep inside a galactic potential well. In NGC 4330 and NGC 4402, the CO velocity gradients are quite distinct in the receding and the approaching side, an asymmetry also observed in HI.
In the outer part of NGC 4330 and NGC 4402 (the CO clump and the modest CO bump, respectively) where the molecular gas is off from the mid-plane, we also find the velocity gradient deviates from the overall gas flow of the gas disc.
Molecular gas mass does not necessarily change significantly during and after severe HI stripping, while its detailed molecular gas properties may change.

Основные выводы

- In summary, our results suggest that a strong ICM pressure not only strips diffuse atomic gas but also changes the properties of dense molecular gas in the inner few kpc of a galaxy. Molecular gas can be pushed from the stellar disc in the outer part as reported in previous studies, yet we find that molecular gas is less likely to be completely stripped from a galaxy. On the side where the ICM pressure acts, molecular gas can be enhanced by compression and molecular formation from atomic gas, locally increasing star formation.
- Both FUV and Ha are enhanced where HI and CO are compressed, supporting that ram pressure can also trigger star formation. However, FUV shows distinct morphology and extent from those of CO, while Ha and CO are overall in good agreement . It must indicate the star formation has been recently quenched, likely over the last 100 Myr