Possible origins of anomalous H I gas around MHONGOOSE galaxy, NGC 5068

J. Healy,[1] ⋆, W.J.G. de Blok,[1,2,3], F.M. Maccagni[1,4], P. Amram[5], L. Chemin[6], F. Combes[7,8], B.W. Holwerda[9], P. Kamphuis[10], D.J. Pisano[3], E. Schinnerer[11], K. Spekkens[12,13], L. Verdes-Montenegro[14], F. Walter[11], E.A.K. Adams[1,2], B.K. Gibson[15], D. Kleiner[1,4], S. Veronese[1,2], N. Zabel[3], J. English[16] and C. Carignan[3,17,18]

ABSTRACT

The existing reservoirs of neutral atomic hydrogen gas (H I) in galaxies are insufficient to have maintained the observed levels of star formation without some kind of replenishment. This refuelling of the H I reservoirs is likely to occur at column densities an order of magnitude lower than previous observational limits ($N_{HI,limit} \sim 10^{19}$ cm^{-2} at 30″ resolution over a linewidth of 20 km s^{-1}). In this paper, we present recent deep H I observations of NGC 5068, a nearby isolated star-forming galaxy observed by MeerKAT as part of the MHONGOOSE survey. With these new data, we are able to detect low column density H I around NGC 5068 with a 3σ detection limit of $N_{HI} = 6.4 \times 10^{17}$ cm^{-2} at 90″ resolution over a 20 km s^{-1} linewidth. The high sensitivity and resolution of the MeerKAT data reveal a complex morphology of the H I in this galaxy – a regularly rotating inner disk coincident with the main star-forming disk of the galaxy, a warped outer disk of low column density gas ($N_{HI} < 9 \times 10^{19}$ cm^{-2}), in addition to clumps of gas on the north west side of the galaxy. We employ a simple two disk model that describe the inner and outer disks, and are able to identify anomalous gas that deviates from the rotation of the main galaxy. The morphology and the kinematics of the anomalous gas suggest a possible extra-galactic origin. We explore a number of possible origin scenarios that may explain the anomalous gas, and conclude that fresh accretion is the most likely scenario.

NGC 5068

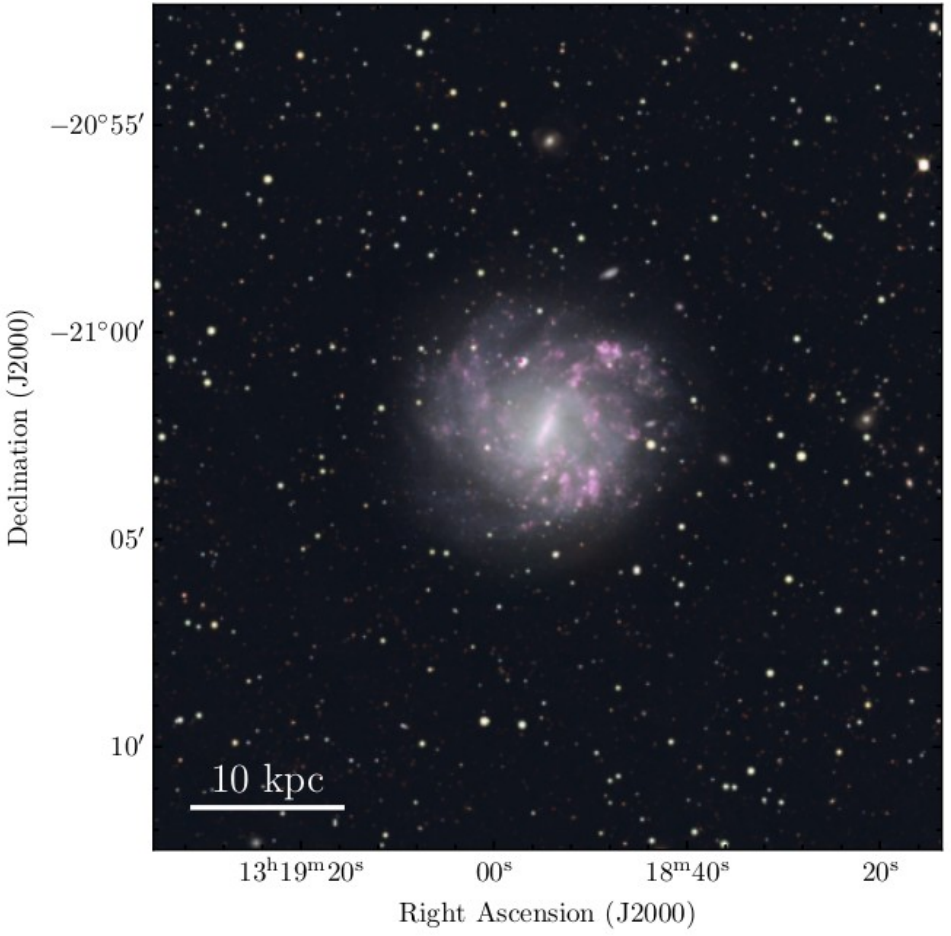


Fig. 1. Composite optical/FUV image of NGC 5068. The DECam Legacy Survey (DECaLS; Dey et al. 2019) *g*,*r*,*z* provides the RGB colour. The far UV observed by GALEX as part of the SUNGG Survey (Wong et al. 2016) highlights the pink star formation regions.

Table 1. General properties of NGC 5068.

α, δ (J2000)	$13^h18^m54.5^s$ −21°02′17″
v_{sys} (km s^{-1})	667.8 ± 1.3[a]
PA (°)	342.4 ± 3.2[b]
i (°)	35.7 ± 10.9[b]
D_{25} (′)	7.03[c]
d (Mpc)	5.20 ± 0.22[d]
M$_\star$ (M$_\odot$)	2.29×10^9 [e]
SFR (M$_\odot$/year)	0.275 ± 0.127 [e]

Notes: [a] calculated from the global profile in this work, [b] based on optical properties from Lang et al. (2020), [c] *B*-band diameter at 25 mag /arcsec^2 isophote from Lauberts & Valentijn (1989), [d] TRGB from Anand et al. (2021), [e] Leroy et al. (2019)

Наблюдения

MeerKAT 5.5x10
(50 часов на объекте) + Магия обработки

Table 2. Properties of the H I cubes.

Cube	Resolution (arcsec × arcsec)	Pixel size (arcsec)	$\sigma^{a}_{\rm rms}$ (mJy/beam)	$N_{H\,I}$ (3σ over 20 km s^{-1})^{c} (cm^{-2})	$N_{H\,I}$ (S/N= 3)^{d} (cm^{-2})
$r = 0.0$, $t = 0''^{b}$	8.1×6.9	2	0.215	6.8×10^{19}	9.1×10^{19}
$r = 0.5$, $t = 0''$	13.4×9.4	3	0.169	2.3×10^{19}	3.1×10^{19}
$r = 1.0$, $t = 0''$	26.0×17.9	5	0.148	5.6×10^{18}	6.5×10^{18}
$r = 1.5$, $t = 0''$	34.3×25.6	7	0.153	3.1×10^{18}	3.4×10^{18}
$r = 0.5$, $t = 60''$	65.3×63.8	20	0.241	1.0×10^{18}	1.1×10^{18}
$r = 1.0$, $t = 90''$	93.8×91.7	30	0.313	6.4×10^{17}	7.0×10^{17}

Notes: [a] this is measured per 1.4 km s^{-1} channel. [b] r is the robust weighting, and t the Gaussian taper. [c] based on 3σ detection in 14 channels. [d] mean column density at the S/N=3 contour in the moment 0 map, see Section 3.1 for details.

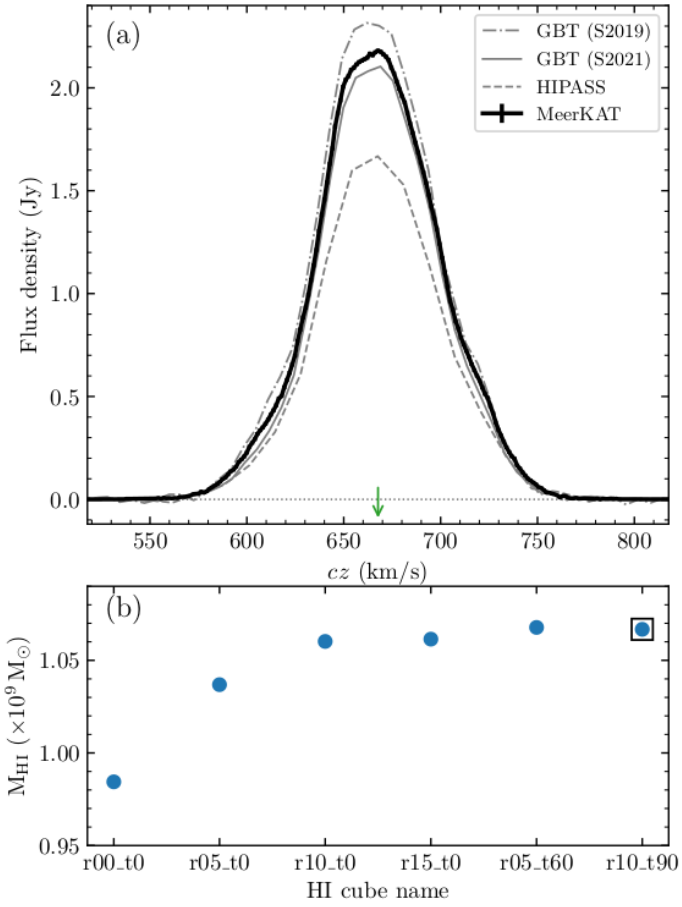
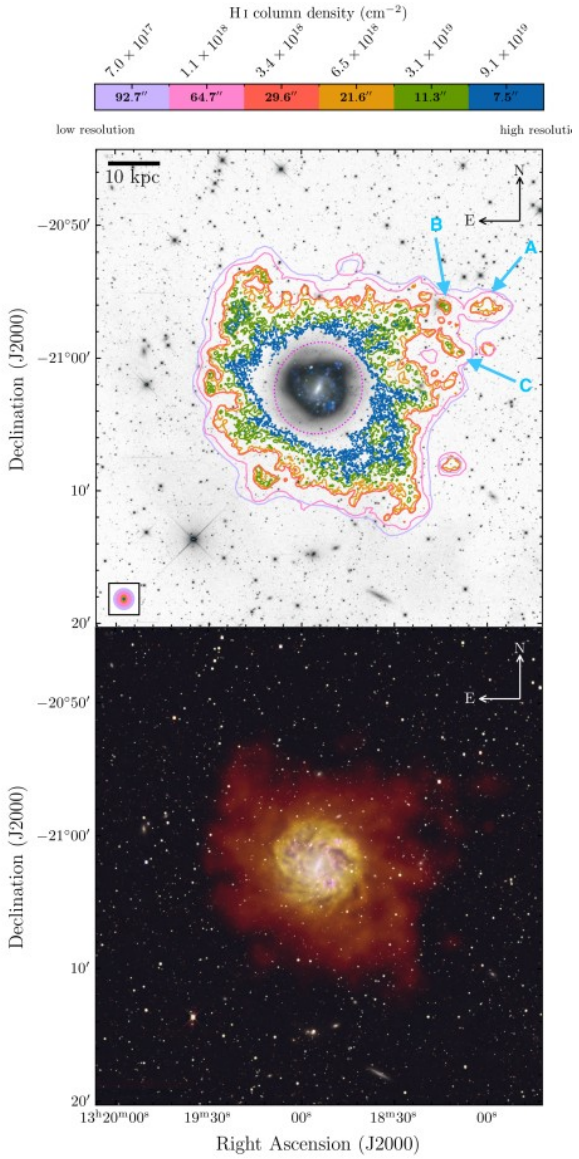


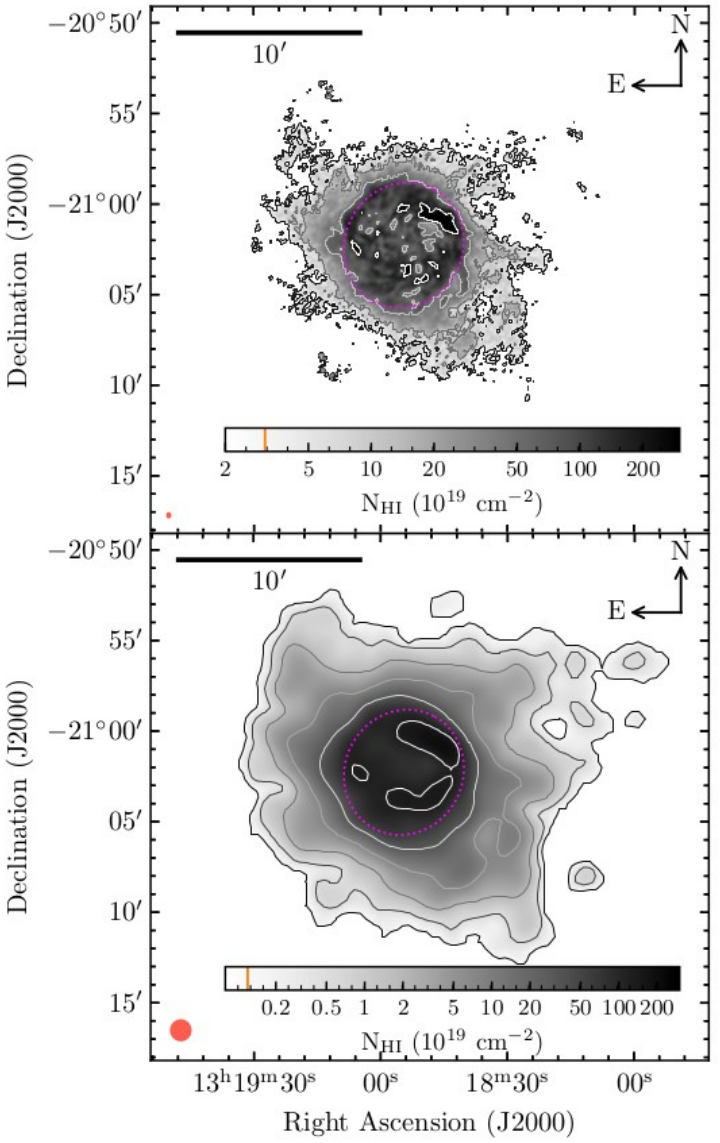
Fig. 5. (a) Global H I profile of NGC 5068 from MeerKAT (black), HIPASS (dashed grey; Koribalski et al. 2004), GBT (solid grey and dot-dash grey; Sorgho et al. 2019; Sardone et al. 2021). The green arrow indicates the systemic velocity of the galaxy. (b) The H I mass of NGC 5068 measured within the `SoFiA-2` mask for each different resolution cube. The open black square indicates which cube was used to create the global profile shown in the top panel.

Глобальные характеристики NGC 5068

Table 3. Global H I properties of NGC 5068 measured from the global profile.

Parameter	Value
S_{int}	$167.82 \pm 0.15\,\mathrm{Jy\,km\,s^{-1}}$
$M_{H\,I}$ (total)	$1.07 \pm 0.09 \times 10^9\,M_\odot$
w_{50}	$67.1 \pm 0.6\,\mathrm{km\,s^{-1}}$
w_{20}	$109.1 \pm 2.0\,\mathrm{km\,s^{-1}}$
v_{sys}	$667.8 \pm 1.3\,\mathrm{km\,s^{-1}}$


H I column density (cm^{-2})
7.0×10^{17}
1.1×10^{18}
3.4×10^{18}
6.5×10^{18}
3.1×10^{19}
9.1×10^{19}
92.7″
64.7″
29.6″
21.6″
11.3″
7.5″
low resolution
high resolution
10 kpc
N
E
A
B
C
D
Declination (J2000)
−20°50′
−21°00′
10′
20′
13h20m00s
19m30s
00s
18m30s
00s
Right Ascension (J2000)


10′
N
E
2 5 10 20 50 100 200
N_{HI} (10^{19} cm^{-2})
0.2 0.5 1 2 5 10 20 50 100 200
N_{HI} (10^{19} cm^{-2})
Declination (J2000)
−20°50′
55′
−21°00′
05′
10′
15′
13h19m30s
00s
18m30s
00s
Right Ascension (J2000)

Кинематика газа

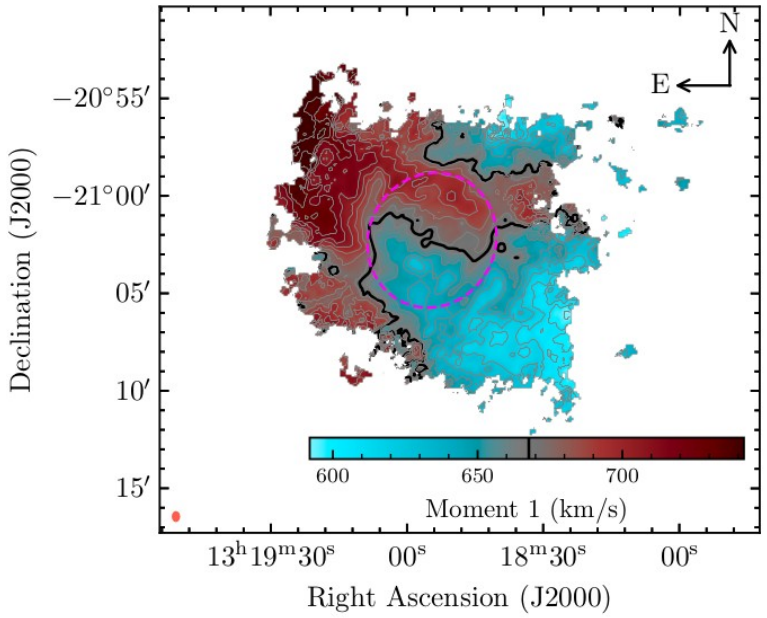


Fig. 6. Velocity field (moment 1) for NGC 5068. Pixels with an H I column density below $N_{H\,I} = 5.9 \times 10^{18}$ cm^{-2} (S/N=3) are masked. The colourbar in the bottom of the image indicates the velocity of the gas, the grey contours are spaced 10 km s^{-1} apart with the black contour indicating the systemic velocity, $v_{sys} = 667$ km s^{-1}. The dotted magenta ellipse is centred on the optical centre of the galaxy and represents the optical size of the galaxy.

- (1) a regularly rotating inner disk with a mass measured within the Σ H i = 1 $M_\odot$ pc^{-2} contour of $M_{disk} = 9.7 \times 10^8$ $M_\odot$;
- (2) a separate, inclined warped “disk” which extends to larger radii than the optical disk, that has an H i mass of M outer = 8.9×10^7 $M_\odot$, calculated as all the H i outside the inner disk (including the 3rd component);
- (3) the north/north western quadrant which is home to the clumpy clouds identified in Fig. 2 which make up on average 8.9×10^4 $M_\odot$ each, with the most massive being C at 1.6×10^5 $M_\odot$.

Table 5. H I mass measurements of the different components of the H I disk of NGC 5068.

Component	H I mass ($M_\odot$)
$M_{H\,I,\,total}$	1.07×10^9
M_{disk}	9.7×10^8
M_{outer}	8.9×10^7
Average M_{clumps}	8.9×10^4
$M_{H\,I}$ (residual clumpy gas)	2.6×10^7

Кинематика газа

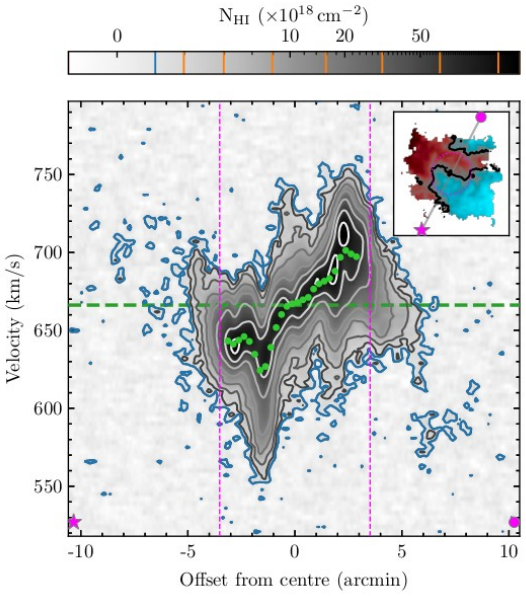


Fig. 7. Position-velocity diagram extracted with a width of 21.6″ which corresponds to the size of the beam. The slice is extracted along optical major axis. The inset on the top right of the figure shows the velocity field from Fig. 6, the grey line running from the magenta star to the filled circle represent the path along which the PV slice was extracted, the magenta star and circle are located in the lower left and upper right corners indicating the direction of the slice, these symbols are repeated lower left and right corners of the main figure. The horizontal dashed green line indicates the systemic velocity, while the light green filled circles show the moment 1 velocity at each position along the major axis. The dashed vertical magenta lines correspond to the edge of the optical disk represented by the dotted magenta ellipse in the inset. The blue and orange contours in the colour bar correspond to the blue and greyscale contours on the PV slice.

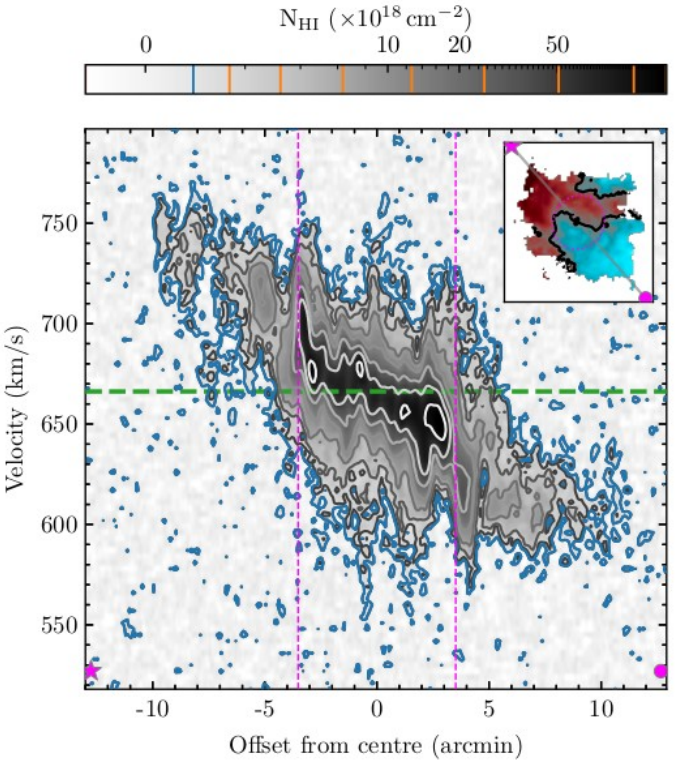


Fig. 8. Same as Fig. 7 but at an angle of 224° through the outer disk.

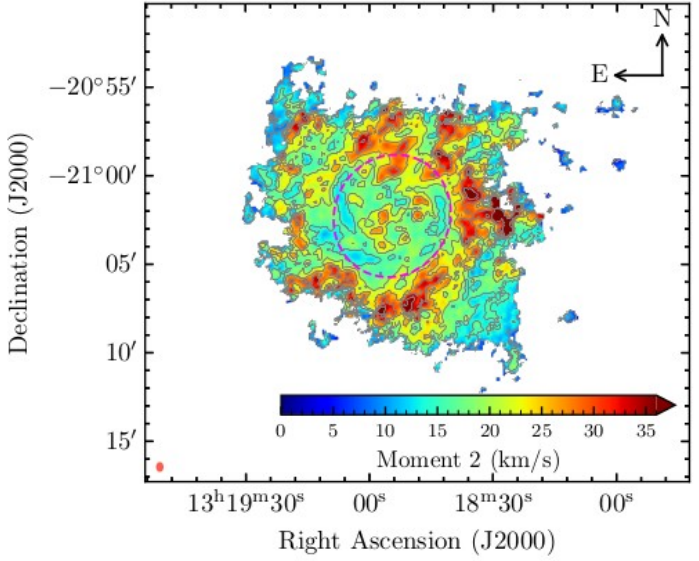


Fig. 9. Moment 2 map for NGC 5068 at 21.6″ resolution. Pixels with an H I column density below the S/N=3 threshold of $N_{HI} = 5.9 \times 10^{18}$ cm^{-2} are masked. The colourbar in the bottom of the image indicates the moment 2 velocity of the gas, the thin grey contours are spaced 5 km s^{-1} apart. The dotted magenta ellipse is centred on the optical centre of the galaxy and represents the optical size of the galaxy.

Происхождение “кольца” с высокой дисперсией скоростей

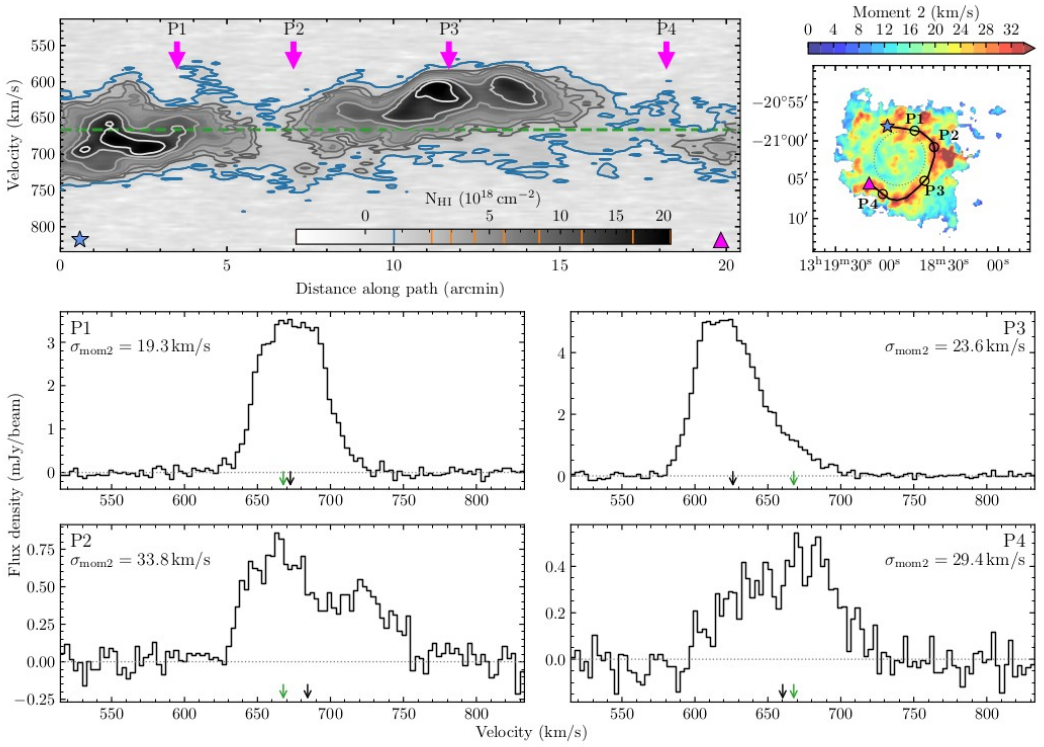


Fig. 10. Top left: Position-velocity (PV) diagram through the high moment 2 region of NGC 5068. The blue and orange lines in the grayscale colourbar correspond to the blue and grayscale contours. The green dashed line indicates the systemic velocity. Top right: moment 2 map of the galaxy with the black line tracing the path along which the PV slice was extracted, starting from the blue star and ending at the magenta triangle. Bottom: H I line profiles extracted at different locations along the PV slice, the extracted locations are indicated by the magenta arrows in the PV diagram. The location of each spectrum is also indicated by the labelled open circles on the moment 2 map. Green arrows at the bottom of the line profiles indicate the systemic velocity of the galaxy, while the black arrows point to the moment 1 velocity.

Наложение двух дисков на луче зрения? => нужна модель вращения галактики.

Остатки после вычитания модели вращения. => клампы

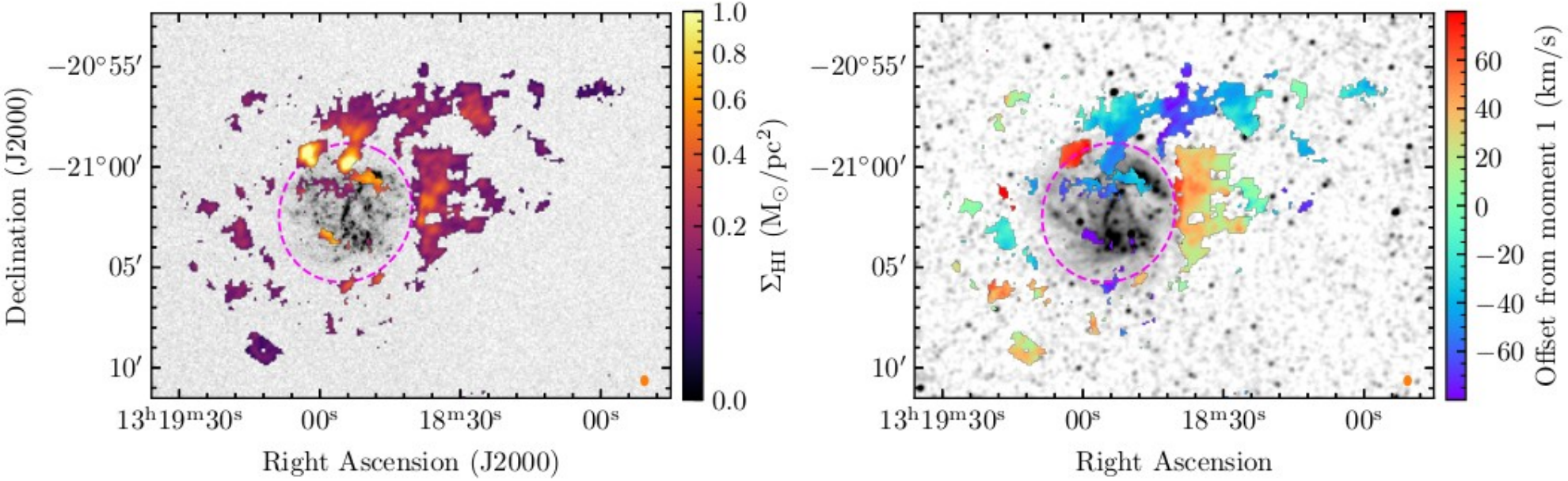
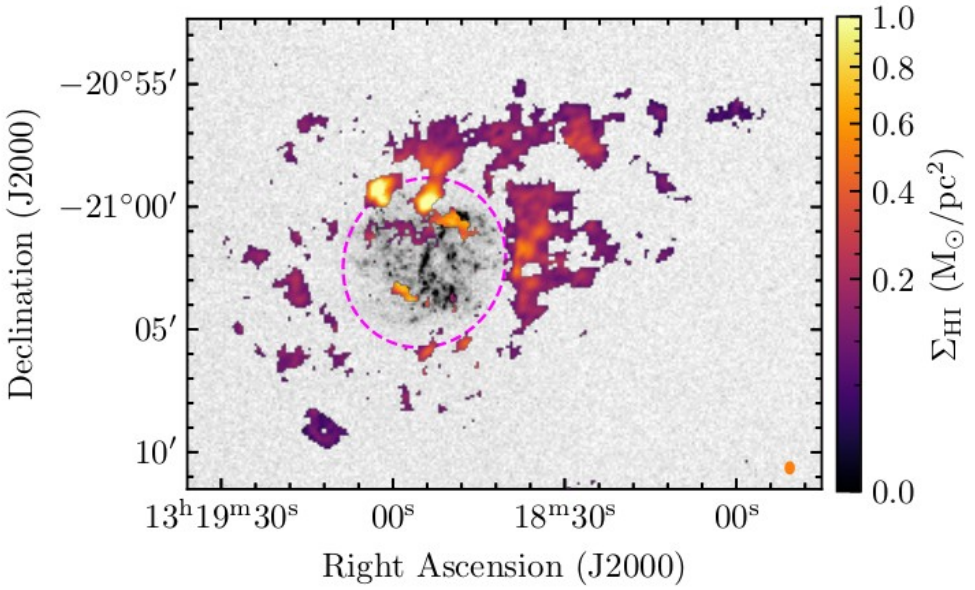


Fig. 12. Left: H I gas surface density of the clumpy gas not contained in the model overlaid on an GALEX FUV image of NGC 5068. Right: the velocity field of the clumpy gas overlaid on the MeerKAT continuum image, the colour shows difference in moment 1 velocity of the clumpy gas and the total velocity field shown in Fig. 6

Происхождение клампов



- Interactions with nearby group galaxies (Галактика практически изолированна)
- Stripped gas from a passing neighbour (Не нашли соседа)
- Minor merger with a gas rich galaxy (Объясняет диск, но не клампы)
- Fountain triggered accretion (Ожидаем повышенную металличность во внешних областях)
- Accretion of gas along a filament (Самый подходящий вариант)