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# Unusual Gas Structure in an Otherwise Normal Spiral Galaxy Hosting GRB 171205A/SN 2017iuk

M. Arabsalmani<sup>1,2,11</sup> , S. Roychowdhury<sup>3</sup> , F. Renaud<sup>4</sup>, A. Burkert<sup>3,5</sup> , E. Emsellem<sup>6,7</sup> , E. Le Floch<sup>8,9</sup>, and E. Pian<sup>10</sup>

<sup>1</sup> Excellence Cluster ORIGINS, Boltzmannstraße 2, D-85748 Garching, Germany; [maryam.arabsalmani@origins-cluster.de](mailto:maryam.arabsalmani@origins-cluster.de)

<sup>2</sup> Ludwig-Maximilians-Universität, Schellingstraße 4, D-80799 München, Germany

<sup>3</sup> University Observatory Munich (USM), Scheinerstraße 1, D-81679 München, Germany

<sup>4</sup> Department of Astronomy and Theoretical Physics, Lund Observatory, Box 43, SE-221 00 Lund, Sweden

<sup>5</sup> Max-Planck-Institut für extraterrestrische Physik (MPE), Giessenbachstr. 1, D-85748 Garching, Germany

<sup>6</sup> European Southern Observatory, Karl-Schwarzschild-Straße 2, D-85748 Garching, Germany

<sup>7</sup> Univ. Lyon, Univ. Lyon1, ENS de Lyon, CNRS, Centre de Recherche Astrophysique de Lyon, UMR5574, F-69230 Saint-Genis-Laval, France

<sup>8</sup> IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

<sup>9</sup> Université Paris Diderot, AIM, Sorbonne Paris Cité, CEA, CNRS, F-91191 Gif-sur-Yvette, France

<sup>10</sup> INAF, Astrophysics and Space Science Observatory, via P. Gobetti 101, I-40129 Bologna, Italy

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## Abstract

We study the structure of atomic hydrogen (HI) in the host galaxy of GRB 171205A/SN 2017iuk at  $z = 0.037$  through HI 21 cm emission line observations with the Karl G. Jansky Very Large Array. These observations reveal unusual morphology and kinematics of the HI in this otherwise apparently normal galaxy. High column density, cold HI is absent from an extended North–South region passing by the optical center of the galaxy, but instead is extended toward the South, on both sides of the galaxy. Moreover, the HI kinematics do not show a continuous change along the major axis of the galaxy as expected in a classical rotating disk. We explore several scenarios to explain the HI structure and kinematics in the galaxy: feedback from a central starburst and/or an active galactic nucleus, ram-pressure stripping, accretion, and tidal interaction from a companion galaxy. All of these options are ruled out. The most viable remaining explanation is the penetrating passage of a satellite through the disk only a few Myr ago, redistributing the HI in the GRB host without yet affecting its stellar distribution. It can also lead to the rapid formation of peculiar stars due to a violent induced shock. The location of GRB 171205A in the vicinity of the distorted area suggests that its progenitor star(s) originated in extreme conditions that share the same origin as the peculiarities in HI. This could explain the atypical location of GRB 171205A in its host galaxy.

*Unified Astronomy Thesaurus concepts:* [Gamma-ray bursts \(629\)](#); [Type Ic supernovae \(1730\)](#); [Interstellar medium \(847\)](#); [Galaxy dynamics \(591\)](#); [Galaxy kinematics \(602\)](#); [H I line emission \(690\)](#); [Galaxy interactions \(600\)](#)

## 1. Introduction

The large-scale dynamics of star-forming galaxies can be traced through the distribution and kinematics of their atomic hydrogen (HI) reservoirs. This is particularly so because the HI reservoir of star-forming (both spiral and dwarf) galaxies typically extend much beyond their stellar disks (Begum et al. 2008; Walter et al. 2008). This extended HI helps register signatures of varied dynamical mechanisms like tidal interactions and mergers (e.g., Sancisi 1999), gas infall (e.g., Sancisi et al. 2008), and various mechanisms that can affect the content, distribution, and kinematics of gas in galaxies in group and cluster environments (e.g., see Chung et al. 2009 for a detailed discussion on such mechanisms).

Recent studies indicate a possible link between rare galaxy dynamics and the extreme conditions that ignite the bright explosions of massive stars: long-duration gamma-ray bursts (GRBs), commonly associated with energetic supernovae (SNe), and superluminous SNe (Arabsalmani et al. 2019a, 2019b; Roychowdhury et al. 2019). These energetic events are believed to occur at the end of the life-cycle of extremely

massive stars ( $M \gtrsim 40 - 100 M_{\odot}$ ) and are therefore quite rare (see Woosley & Heger 2006; Gal-Yam 2012, and references therein). The study of HI structure in the closest known GRB host (GRB 980425/SN 1998bw,  $z = 0.0087$ ) revealed it to be a collisional ring galaxy, with the GRB residing within the ring (Arabsalmani et al. 2015, 2019a). Such rings are ideal places for formation of massive star clusters in which very massive stars could form. The resolved molecular gas studies of the host galaxy showed the presence of local starburst modes of star formation (Arabsalmani et al. 2020), again ideal for formation of massive star clusters. Roychowdhury et al. (2019) found the mysterious transient AT2018cow ( $z = 0.0141$ ) to be also within a broken-ring of HI in its host galaxy. Furthermore, Arabsalmani et al. (2019b) found the location of SLSN PTF10tpz ( $z = 0.0399$ ) to be within very dense gas clouds, formed by the interaction of gas flows and due to the dynamics of the bar in the host galaxy. Such rare dynamics (due to external/internal effects) could be the factors singling out the host galaxies of these bright transients, and result in the formation of their massive progenitor stars. In other words, these rare and energetic transients could be the tracers of gas-rich galaxies with extreme dynamics.

In this paper we present a detailed study of HI in the host galaxy of GRB 171205A/SN 2017iuk at  $z = 0.037$  through the observations of HI 21 cm emission line with the Karl G. Jansky Very Large Array (JVLA) in B configuration. This is the second nearest GRB associated with a supernova, and is

<sup>11</sup> Vera Rubin Fellow.

located in the outskirts of its large, spiral host galaxy, identified as 2MASX J11093966-1235116 (LCRS B110709.2-121854) in optical surveys (Shectman et al. 1996; Izzo et al. 2017; Wang et al. 2018). With a stellar mass of  $10^{10.1\pm 0.1} M_{\odot}$ , a star formation rate of  $\sim 1-3 M_{\odot} \text{ yr}^{-1}$ , and a solar metallicity (Perley & Taggart 2017; Wang et al. 2018), the host galaxy is among the main sequence galaxies and follows the mass–metallicity relation of star-forming galaxies in the local Universe (Brinchmann et al. 2004; Tremonti et al. 2004). It therefore seems to be a typical star-forming galaxy, hosting a GRB in the nearby Universe, thus an enigmatic case to study.

We describe the details of observations and data reduction in Section 2. The results and a detailed discussion are presented in Section 3. We summarize our findings in Section 4. Throughout this paper we use a flat  $\Lambda$ CDM with  $H_0 = 70 \text{ k s}^{-1} \text{ Mpc}^{-1}$  and  $\Omega_m = 0.3$ .

## 2. Observations and Data Analysis

We used the *L*-band receivers of the JVLA in B configuration to map the HI 21 cm emission from the host galaxy of GRB 171205A. The observations were carried out on 2019 March 09 and 2019 May 05 for a total time of  $\sim 10.5$  hr (proposal ID: VLA/19A-394; PI: Arabsalmani). The observations used the JVLA Software Backend with 16 MHz bandwidth, centered on  $\sim 1.368$  GHz, subdivided into 4096 channels, yielding a velocity resolution of  $\sim 0.9 \text{ km s}^{-1}$  and a total velocity coverage of  $\sim 3500 \text{ km s}^{-1}$ . Two orthogonal linear polarizations were observed, data from which were combined for obtaining the final result. The bright calibrator 3C286 was observed at the start of each observing run, to calibrate the flux and the system bandpass. The secondary calibrator J1130-1449 was also observed intermittently in order to calibrate the time dependent part of the gain and the system bandpass.

“Classic” AIPS was used for the analysis of the data (Greisen 2003). The first step was a flagging and calibration loop during which bad visibilities were identified and flagged separately for each of the linear polarizations, following which the antenna-based complex gains were calibrated. Thereafter system bandpasses were estimated and calibrated for each day’s data set separately. After this, the calibrated data from both the days were combined together.

From the combined data set initially a “channel-averaged” visibility data set was created by averaging together line-free channels, which was used for a standard continuum imaging and self-calibration loop. 3D imaging was performed on the channel-averaged visibilities with the task IMAGR using 2D facets, completely covering a circular area of diameter  $1^{\circ}.1$  around the phase center. Imaging was also performed over  $0.7$  MHz wide channels in order to avoid bandwidth smearing, with the final image produced by averaging the channel-based images. The total continuum flux was measured to be  $\sim 193$  mJy. We do not detect any continuum emission from the GRB host galaxy, but we detect the continuum emission from SN 2017iuk/GRB 171205 and measure its flux density to be  $2.99 \pm 0.12$  mJy using 2D Gaussian fitting (consistent with the measurements presented in Leung et al. 2021). At the end of the continuum imaging and self-calibration loop, the final antenna-based gains were applied to all the visibilities of the original multichannel combined data set.

The radio continuum image made using the line-free channels at the end of the self-calibration cycle was used to

model and subtract the continuum from the calibrated visibilities in the original multichannel data set, using the task UVSUB. Any residual spectral baseline across the observed band was then removed using the task UVLIN. We used these residual visibilities after continuum subtraction to create a spectral cube using the task IMAGR, where the imaging was restricted to the central quarter of the JVLA primary beam. The velocity resolution of the cube was optimized to be  $\sim 34 \text{ km s}^{-1}$  to improve the statistical significance of the detected HI 21 cm emission in independent velocity channels while still having sufficient resolution to accurately trace the velocity field. In order to optimize between the signal-to-noise ratio of the detection and the spatial resolution, a robust factor of 0.5 was used to create the cube. The synthesized beam for the cube has a full width at half maximum (FWHM) of  $7''.1 \times 6''.3$ . We reach the theoretical rms-noise of  $\sim 0.2$  mJy per beam in each  $34 \text{ km s}^{-1}$  channel.

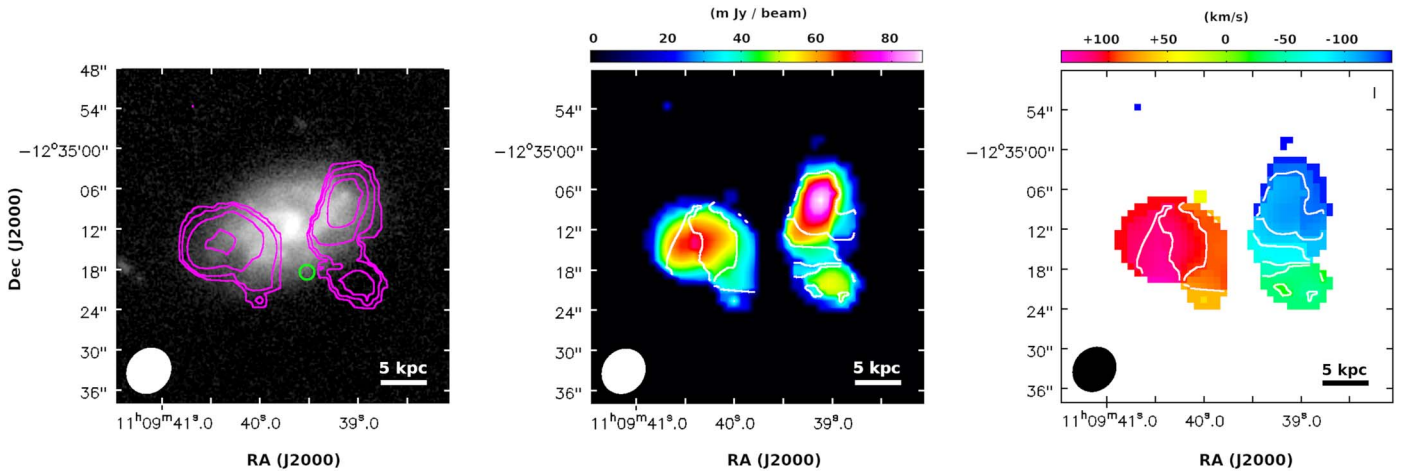
We apply the task MOMNT to the spectral cube in order to obtain maps of the HI total intensity and the intensity-weighted velocity field for each detected source. MOMNT works by masking out pixels in the spectral data cube which lie below a threshold flux in a secondary data cube which the task creates internally within AIPS by smoothing the original cube both spatially and along the velocity axis—the smoothing ensures that any localized noise peaks are ignored and only emission correlated spatially and in velocity is chosen. MOMNT created the secondary data cube by applying Hanning smoothing across blocks of three consecutive velocity channels, whereas spatially a Gaussian kernel of FWHM equal to twelve pixels (about twice the size of the synthesized beam) was applied. The threshold flux used to select pixels was approximately 1.3 times the noise in a line-free channel of the original cube, a threshold at which noise peaks just start to show up in the total intensity map. Using the total-intensity map of HI we identified the region of emission and obtain the HI spectrum from the cube. We measured the integrated flux density of HI 21 cm emission line by integrating over the adjacent channels with fluxes above the rms noise, and converted it to the HI mass.

We also use the *r*-band image of the field of the GRB host galaxy from the Pan-STARRS1 data archive.

## 3. Results and Discussion

We detect the HI 21 cm emission line from the host galaxy of GRB 171205A at  $10\sigma$  significance, centered on a redshift of  $z = 0.0371 \pm 0.0001$ . We measure an integrated flux density ( $S\Delta\nu$ ) of  $0.486 \pm 0.048 \text{ Jy km s}^{-1}$  and obtain an HI mass of  $10^{9.49\pm 0.04} M_{\odot}$  for the host galaxy. With a stellar mass of  $10^{10.1\pm 0.1} M_{\odot}$ , the host galaxy has a  $M_{\text{HI}}/M_{*}$  of 0.2, the average value for nearby star-forming galaxies with similar stellar masses (Catinella et al. 2018). Moreover, the HI 21 cm line width of  $\sim 300 \text{ km s}^{-1}$ , measured at the 50% level of the peak flux, places the GRB host galaxy on the Tully-Fisher relation in the local Universe (McGaugh 2012).

Figure 1 shows the intensity and velocity maps of HI 21 cm emission in the host galaxy of GRB 171205A. Given that the detection limit in our observations corresponds to a column density of  $5 \times 10^{20} \text{ cm}^{-2}$  at  $3\sigma$  significance, we expect the detected HI to be in the “cold neutral phase” with temperatures of a few hundred Kelvins (Kanekar et al. 2011). The distribution of this cold HI in the host galaxy has a butterfly-shape. The gas associated with the optical disk forms the Northern parts of the wings. The Southern parts consist of



**Figure 1.** Left panel: contours of H I 21 cm emission line overlaid on the *R*-band Pan-STARRS image of GRB 171205A host galaxy. The outermost contour marks the  $3\sigma$  level of emission in a single channel (with a velocity width of  $34 \text{ km s}^{-1}$ ). This is equivalent to a H I column density of  $5 \times 10^{20} \text{ cm}^{-2}$ . Each subsequent contour is in multiples of  $\sqrt{2}$ . The green circle marks the position of GRB 171205A. Middle panel: total intensity map of H I 21 cm emission line in color, overlaid with contours of the velocity map of H I 21 cm emission line for GRB host. The velocity contours in the left butterfly wing mark the velocities of  $+115$ ,  $+95$ , and  $+75 \text{ km s}^{-1}$  from left to bottom right. In the right butterfly wing, the contours mark the velocities of  $-25$ ,  $-45$ ,  $-65$ ,  $-85$ ,  $-105$ , and  $-125 \text{ km s}^{-1}$  from bottom left to top. Right panel: the intensity-weighted velocity map of H I 21 cm emission line in color, overlaid with velocity contours as in the middle panel. The size of the images in all panels are  $50'' \times 50''$ . The synthesized beam of JVLA observations is shown in the bottom-left corners of the maps.

extensions of gas outwards of the optical disk of the host where the main disk has no detectable stellar extension. These extensions contribute to more than 20% of the total H I mass in the galaxy.

Cold H I is absent from an extended north–south region passing by the optical center of the galaxy. The depression of H I in the center of galaxies has been typically observed in nearby spirals and is generally thought to result from the conversion of atomic gas to molecular gas in the central regions (Walter et al. 2008). However, the depression is quite unusual in the host galaxy of GRB 171205A: it is not limited to only the center of the galaxy, and it is also spread over almost half of the velocity width of the H I. Deeper observations are planned to confirm the absence of H I at lower column densities in this region. Unlike the case of GRB 980425 and AT2018cow (Arabsalmani et al. 2015, 2019a; Roychowdhury et al. 2019), GRB 171205A is not located within the high column density H I ( $>5 \times 10^{20} \text{ cm}^{-2}$ ) in its host galaxy (see the left panel of Figure 1 where the GRB position is marked with a green circle). It is instead located close to the east of the western butterfly wing, a side in which the concentration of H I contours have a sharp edge, suggesting a shock in the cold H I.

The velocity field of H I in the butterfly-shaped distribution does not show the classical pattern of rotation. Gas in the eastern wing is moving away from us, with its velocity in the rest frame of the galaxy decreasing from left to the bottom right. Gas in the western wing is moving toward us, with its velocity in the rest frame of the galaxy increasing from bottom-left to top. Had the gas been in a rotating disk, we would have seen a continuous change of velocity along an east–west axis going through the center of the galaxy.

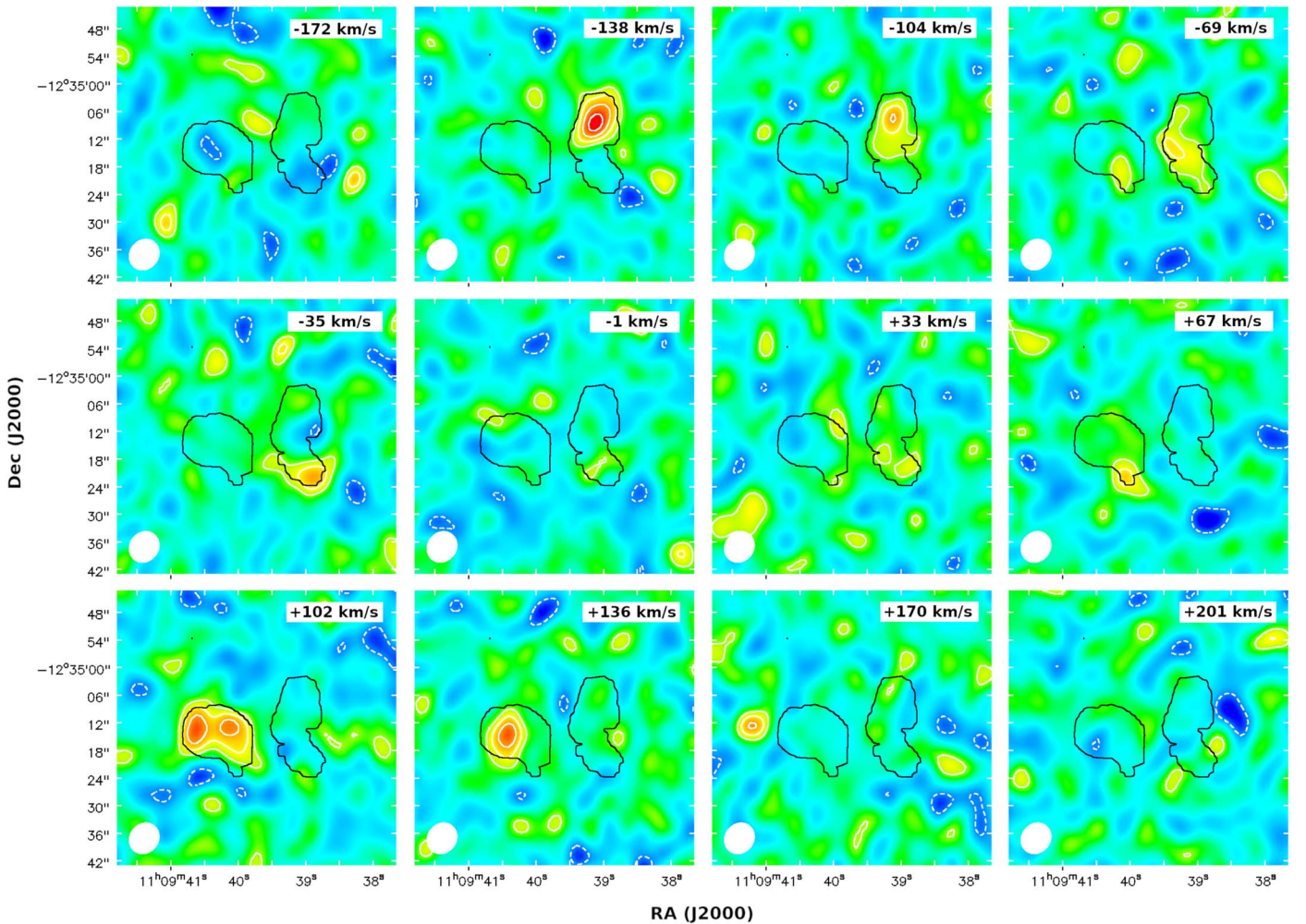
This can be better seen in the individual channel maps in Figure 2. The gas associated with the optical disk of the galaxy (the northern parts of the wings) corresponds to a rotating disk, though with missing gas over a large velocity range. This component is clearly detected in four channels with central velocities of  $-138$ ,  $-104$ ,  $+102$ , and  $+136 \text{ km s}^{-1}$ , but is not present in four channels with central velocities of  $-35$ ,  $-1$ ,  $+33$ , and  $+67 \text{ km s}^{-1}$ . The missing gas therefore covers about

$150 \text{ km s}^{-1}$  in velocity space. This is an unusually large velocity window considering that the whole velocity spread of this galaxy is about  $300 \text{ km s}^{-1}$  (see for e.g., Walter et al. 2008).

In order to investigate whether the high column density sensitivity limit of our observations can explain the observed "piling up" of H I in a narrow range of velocities at the edges in the channel maps, we created models of a rotating H I disk with a flat rotation curve at the edges. Using the GALMOD task in Gipsy64 (van der Hulst et al. 1992) we simulated a rotating H I disk of uniform density and velocity dispersion with large flattened part of the rotation curve at the edges of the disk. We found that irrespective of the inclination angle, even with a large amount of gas in the outskirts in the flat rotation curve regime, high column density H I should be visible in the central channels owing to projection effects, unlike what we see in our observed channel map. We also simulated a ring of H I gas with no H I present in the inner  $2/3$ s and with the outer part having almost a flat rotation curve, again with uniform column density and velocity dispersion. Even for such an extreme case, the simulated models showed the presence of high column density H I in the central channels. We therefore confirm that the apparent deficit of H I, associated with the optical disk of the galaxy, in the central channels in Figure 2 is unlikely to be a result of the sensitivity limit of the observations.

The extended gas (the southern part of the wings) is present in channels with central velocities between  $-35$  and  $+33 \text{ km s}^{-1}$  in Figure 2, where H I associated with the optical disk of the galaxy does not show any emission. This makes it difficult to justify that this gas is merely an extension of the gas disk associated with the optical disk of the galaxy. In addition, detection of this component at high column densities ( $5 \times 10^{20} \text{ cm}^{-2}$  at  $3\sigma$  significance), spatially extended over a large area, is unlike what is expected for infalling/accreting gas. It is more likely that an internal/external mechanism has removed the cold H I from the central region of the host and instead has pushed and compressed it toward the southwestern and southeastern sides. This hypothesis is supported by the high column density of the extended gas in the southern parts, and also by the pattern of its velocity being similar to that of the gas





**Figure 2.** The intensity map of the HI 21 cm emission in 12 successive channels. Each map has a size of  $1' \times 1'$  and a velocity width of  $34 \text{ km s}^{-1}$ . The contours of the HI 21 cm intensity are overlaid in white with the dashed contours at  $-2\sigma$  level. The first solid contours are at  $2\sigma$  level, with each subsequent contours increasing by  $1\sigma$ . The black contour marks the total HI 21 cm emission (moment-0) from the host galaxy at  $3\sigma$  significance. The synthesized beam of JVLA observations is shown in the bottom-left corner of each map. The number in the top-left corner of each map is the central velocity of the channel corresponding to the map, relative to the redshift of the galaxy obtained from HI.

associated with the optical disk. Note that the emission detected in channels with central velocities of  $-69$  and  $+102 \text{ km s}^{-1}$  suggests that the gas in the northern and southern parts of either butterfly wing are dynamically connected, even when considering the size of the synthesized beam of the observations.

Feedback from a nuclear starburst in the host galaxy can clear the gas in the central regions and redistribute it toward the southern/northern part of the galaxy. However, the distribution of the  $H\alpha$  emission in the host galaxy suggests the absence of a nuclear starburst (based on the VLT/MUSE observations of the host; C. Thone et al. 2022, in preparation). An active galactic nucleus (AGN) could have a similar effect, though over smaller scales. Nevertheless, the analysis presented in Wang et al. (2018) rules out the presence of an AGN in the GRB host. Other hydrodynamical processes such as ram-pressure stripping do not explain the HI structure in the galaxy. Ram pressure from a dense intergalactic medium typically pushes large parts of the gas disk toward one side of the galaxy relative to the optical disk, determined by the direction of infall of the galaxy toward the local over density. Such an effect cannot selectively remove gas from the center of the galaxy. In any case we note that the host galaxy is not a part of any identifiable group or cluster based on the optical image of the field, which

makes the gas in the galaxy being ram pressure stripped by a dense intergalactic medium an unlikely scenario.

With all above mentioned candidates ruled out, interaction with a companion remains the most viable explanation for the peculiar structure of HI in the host galaxy of GRB 171205A. While classical tidal interactions are expected to result in gas inflows toward the galaxy center (e.g., Renaud et al. 2014), the penetrating passage of a companion through the disk of the GRB host could drag the gas out of the galaxy and result in the observed features in the HI distribution. Such a passage creates a tidal perturbation and leads to large-scale shocks and ram pressure between the gaseous media of the two galaxies. The stellar component is not directly affected by hydrodynamical processes (shocks, ram pressure). But it should respond to the change of gravitational potential induced by the displacement of the gas (in this case more than 20% of the gas budget of the GRB host). Furthermore, the tidal perturbation in gas should also induce disturbances in the stellar component (e.g., a warp, tidal tails). The well-ordered distribution of the stellar component in the GRB host galaxy (see the left panel of Figure 1) therefore suggests that the passage is very recent such that the distribution of stars have not yet been affected.

In the first passage of a low-mass companion, the gas component of the main galaxy, as a continuous medium, immediately reacts to the presence of the companion. However, the stellar component that usually has a higher velocity dispersion (Renaud et al. 2021b) takes slightly longer to shape an organized and coherent structure like tidal tails. A few Myr after the pericentre passage, it could well be that both components experience the tidal effect of the companion, but that only the gas shows a different morphology, while the stars are still being accelerated and are soon to form tidal structures. Such a delay has been seen in simulations of galaxy interactions (e.g., Renaud et al. 2021a). In addition to the mentioned delay, the mass of the companion can play a role: too massive a companion would have affected the stars earlier during its approach, while too light a one would not have created the observed significant disturbance in the gas. An exploration of the parameter space with simulations is required to reach a precise estimate that is out of the scope of this paper, but minor mergers can create the perturbations we seek (Di Matteo et al. 2007; Renaud et al. 2009). Follow-up simulation studies and observations of this system are planned in order to investigate the viability of the passage scenario.

The closest galaxy to the GRB host and thus a possible culprit in the passage scenario, as identified in optical surveys is LEDA 951348. This galaxy, with a redshift of  $z = 0.0369$  obtained from our HI 21 cm observations, is located at a projected distance of  $\sim 190$  kpc to the northwest of the GRB host, too far for a recent encounter with the GRB host. We also search for the presence of HI knots associated with possible companions with no or faint stellar components in the vicinity of the GRB host galaxy. We tentatively detect two HI knots in the western and eastern sides of the GRB host, both at projected distances of about 30 kpc from the center of the host galaxy, but disregard them in our analysis given the low significance of their detection. The closest HI source to the GRB host detected with enough significance is at a projected distance of  $\sim 42$  kpc from the GRB host center, to its northwest, and with no identified optical counterpart. The HI mass of this source ( $10^{8.38 \pm 0.08} M_{\odot}$ ) is sufficient to cause the observed disturbance in the gas disk of the GRB host without yet affecting its stars, but the distance between the HI knot and the GRB host is again too large for a recent encounter and would be consistent with timescales  $\gtrsim 100$  Myr. Even a rapid encounter (with a velocity of  $\sim 500$  km s $^{-1}$ ), which might explain the absence of tidally disturbed gas in the GRB host, needs to have occurred at least 80 Myr ago to explain the  $\sim 40$  kpc distance of the knot.

It is possible that the HI clump in the far southwest of the butterfly wing is the remnant of a companion and the gas that has been displaced from the center of the disk. This clump has a mass of  $10^{8.66 \pm 0.07} M_{\odot}$ , about 15% of the HI mass and 3% of the baryonic mass in the GRB host. With a trajectory roughly running from north to south, and approximately in the plane of the sky, the companion would remove the gas in the central regions and create a shock in the main galaxy. This would explain the sharp edge of the HI distribution on the eastern side of the western wing. It would also cause the discontinuity in the HI velocity field. Though the measured line-of-sight velocity of the gas in the clump is close to zero, it can have a large velocity component in the plane of the sky. Keeping in mind the uncertainties on the inclination of the disk, and of the orbit, an encounter speed of  $\sim 500$  km s $^{-1}$  would be compatible with

a pericentre passage less than 20 Myr ago. In classical tidal interactions, the SFR is only starting to rise this early after the pericentre passage, because most of the gas is still being compressed and the collapse of the gas clouds has just started (e.g., Renaud et al. 2014). But in a collision, the created shock can lead to a much more violent formation of stars. Such extreme physical conditions are compatible with the formation of very massive stars.






GRBs are typically found in the bright H II regions within the central  $\sim$ kpc of their host galaxies (e.g., Fruchter et al. 2006; Lyman et al. 2017). The location of GRB 171205A in the outskirts of its host is therefore quite atypical. This could be explained by the formation of the massive star progenitor(s) of GRB 171205A in extreme conditions created by a violent shock, in the vicinity of the gas clump. Note that the location of GRB 171205A is at the edge of what would be a shock, as indicated by the structure of HI in the galaxy (see Figure 1 where the GRB position is marked with a green circle).

#### 4. Summary

We present a detailed study of the distribution and kinematics of atomic hydrogen in the host galaxy of GRB 171205A through the HI 21 cm emission line observation with the JVLA. While the global properties of stars and gas in the host galaxy of GRB 171205A appear quite normal, the structure of its HI shows very unusual features. HI is absent from an extended north–south region passing by the optical center of the galaxy, but extends outwards the optical disk in the south in both sides, with a clear discontinuity in its velocity field along the major axis of the galaxy. We rule out internal (hydrodynamical) effects as the cause of these peculiarities given the absence of enhanced star formation or an AGN in the center of the galaxy. The absence of gas in the central region of the galaxy and the well-ordered stellar distribution in the GRB host rules out past tidal interactions as the cause. The most viable remaining explanation is a very recent (only a few Myr ago) collisional passage of a companion through the disk of the GRB host such that the distribution of stars have not *yet* been affected. It is possible that the HI clump that we detect in the far southwest of the gas distribution of the GRB host is the remnant of the companion and the gas that has been displaced from the center of the disk. The location of GRB 171205A is consistent with the formation of its progenitor star(s) due the shock induced by the collision that is responsible for the observed peculiar features in the HI, supporting the idea that these rare explosions could be ignited by rare dynamics that result in extreme conditions. Much more detailed studies must be carried out to validate this idea.

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## ORCID iDs

M. Arabsalmani  <https://orcid.org/0000-0001-7680-509X>  
 S. Roychowdhury  <https://orcid.org/0000-0002-5820-4589>  
 A. Burkert  <https://orcid.org/0000-0001-6879-9822>  
 E. Emsellem  <https://orcid.org/0000-0002-6155-7166>  
 E. Pian  <https://orcid.org/0000-0001-8646-4858>

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