MeerChoirs: Preliminary neutral gas kinematics of interacting galaxies in the J1250-20 group

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Abstract. We present preliminary results from our study of the distribution and kinematics of the neutral gas in a low-inclination, late-type galaxy that is residing in a group environment and is undergoing a minor merger. We report the kinematics of the extended, warped, asymmetric, and lopsided HI disc of J1250-20 S1 from the Choir groups sample observed with MeerKAT. The high spatial & spectral resolution, sensitivity, and wide field-of-view of MeerKAT enables us to probe HI in a major extent of the group down to $N_{HI} \sim 3 \times 10^{19}\,cm^{-2}$ with a spatial resolution of $12''$ and a spectral resolution of $5\,km\,s^{-1}$. We see indications of Extra-Planar Gas (EPG), tidal interactions with neighbouring galaxies, lagging rotation in the extended disc, and an HI plume. We also detect five previously unknown dwarfs in the extended field that can potentially be part of the group. Resolved studies of such unique laboratories that encapsulate several key processes of the baryon cycle spanning the Interstellar Medium (ISM), Circumgalactic Medium (CGM), and Intra-Group medium (IGrM) are crucial for constraining galaxy evolution models.

1. Introduction

The hydrogen 21 cm line (hereafter HI) in the radio regime is a remarkable tracer of neutral gas in galaxies; offering unique insights about the structure, kinematics, and dynamics of gas, galaxies, and their environments. The HI discs of galaxies often extend to several times the radii of the optical disc and thus holds the potential to directly study mergers, accretion, interactions, and other environmental effects [1]. High sensitivity observations of lower column density HI makes it possible to study the disc properties farther into the CGM. Furthermore, resolved observations of these discs also provide rotation curves out to large radii, which can probe the underlying dark matter [2]. However, the extended gas distribution is far from a simple axi-symmetric, thin, differentially rotating disc. The outer HI discs of spiral galaxies are known to be warped but the cause, formation, and timescales of these warps is not well-established [1]. Lopsidedness in the morphology and kinematics of HI discs as well as asymmetric global spectral profiles in most cases have been attributed to interactions. The HI disc is also expected to be flared in the outer parts, although, this can only be observed in the Milky-way and highly inclined galaxies. Extra-planar gas (EPG) with radial and vertical velocity lags have also been observed directly in edgeon galaxies [3] and kinematically in certain nearly face-on [4] and intermediately inclined galaxies [5]. EPG in the milky-way has been observed in the form of High-velocity Clouds (HVCs) and Intermediate Velocity Clouds (IVCs) in HI emission and absorption signatures on background QSOs and halo stars [6]. A fraction of the EPG is expected to originate from the stellar disc as galactic fountains and another fraction from accretions stemming from interactions or infall from the cosmic web. Resolved and sensitive observations of galaxies at a range of inclination angles are required to understand the kinematics and origins of EPG. Most of the EPG reported to date have been from observations of highly inclined systems. A low-inclination perspective is required to link structures in the stellar disc with the observed EPG and also to explore various motions in the HI disc with reduced projection effects. The unparalleled combination of high sensitivity, large field of view, and high spatial & spectral resolution offered by MeerKAT makes it the optimal instrument to study HI gas kinematics in nearby galaxies and groups.

MeerChoirs (PI: Moses Mogotsi) is a deep HI study of six nearby groups ($<$ 151 Mpc) selected from the Choirs group sample [7] in the SINGG catalog (Survey for Ionization in Neutral Gas Galaxies; [8]; [9]). SINGG is an optical R-band and Hα imaging follow-up to HIPASS (HI Parkes All-Sky Survey; [10]). The Choir sample consists of late type dominated, gas rich groups that are thought to be in the early stages of assembly. About half of the sample contain two large spirals and a number of dwarf galaxies making them morphological analogs of the local group that are in a more compact state. MeerChoirs will be the deepest and highest resolution HI study of the Choir groups to date. We aim to study the impact of the environment on galaxy evolution by mapping galaxy interactions, detecting previously undetected group members, and looking at the resolved HI-properties of individual galaxies within the groups. This work reports the preliminary kinematic analysis of a low-inclination, late-type galaxy (S1) in the HIPASS J1250-20 group (hereafter J1250). Throughout this work, we use the cosmological parameters from Planck 2018 data $H_0 = 67.7\,\mathrm{km\,s^{-1}Mpc^{-1}}$, $\Omega_m = 0.310$, and $\Omega_\Lambda = 0.69$.

2. HIPASS J1250-20

J1250, within a projected radius of $\sim$ 250 kpc, hosts two large spiral galaxies (ESO575-G006 or S1 and ESO575-G004 or S2), three dwarf galaxies (S3, S4, and S5), and two compact Hα emitters (S6 and S7; [7], Dz19[11]). The selection criteria for the Choir groups employed in [7] was constrained to a $15.5'$ field. The wider field of the groups were studied in Dz21[12] by querying NASA/IPAC Extragalactic Database (NED) for sources in a $\sim 4^\circ$ field around each Choir group and cross matching the obtained catalogue with the 2MASS Extended Source Image Server in order to make a magnitude limited sample. They also use a catalogue of filaments in the local universe curated by [13] to estimate distances to the nearest filament for the Choir Groups. From both these explorations, Dz21[12] conclude that J1250 is embedded in a low density environment and that its distance to the nearest filament is about $\sim$ 4 Mpc. Subsequently, they classify J1250 as an isolated group (See panel (c) and (d) of Appendix H figure 17 in D21). The neutral hydrogen content of the central region of the group, was mapped with ATCA and was presented in Dz19[11]. They report a possible interaction between the HI-rich galaxy, S1 and the HI-poor galaxy, S2. The dwarf galaxy S3 and the compact Hα emitters, S6 and S7 were found to be within the HI envelope of S1. The HI associated with S2 was found to be off-center and gas content of the dwarf galaxy S4 was reported to be associated with S2. They conclude that the ongoing minor merger in S1 and the tidal interaction between S1 and S2 could be responsible for the increased HI content of S1 and the decreased HI content of S2. They also recover an HI mass of $M_{\mathtt{HI}}[M_\odot] = 10.53 \pm 0.2$ for a group distance of 114 Mpc, comparable to the mass of $M_{\mathtt{HI}}[M_\odot] = 10.39 \pm 0.11$ quoted in the HIPASS catalogue for a group distance of 110 Mpc [10]. However, due to the target's declination ($\sim -20^\circ$), the synthesized beam for their observation was unevenly elongated in the direction of the beam major axis ($30.79'' \times 102.8''$) causing spurious emission features as a result of beam smearing. Their observations, although smeared, probe HI down to a column density of $\sim 3.5 \times 10^{19}\,\mathrm{cm}^{-2}$ with a velocity resolution of $15\ \mathrm{km\,s}^{-1}$. They also quote an RMS of 2 mJy beam^{-1} in their created cube. The high noise, low resolution of the data, and the non-uniform beam renders it difficult to extract reliable gas kinematics.

2.1. MeerKAT observations and data reduction

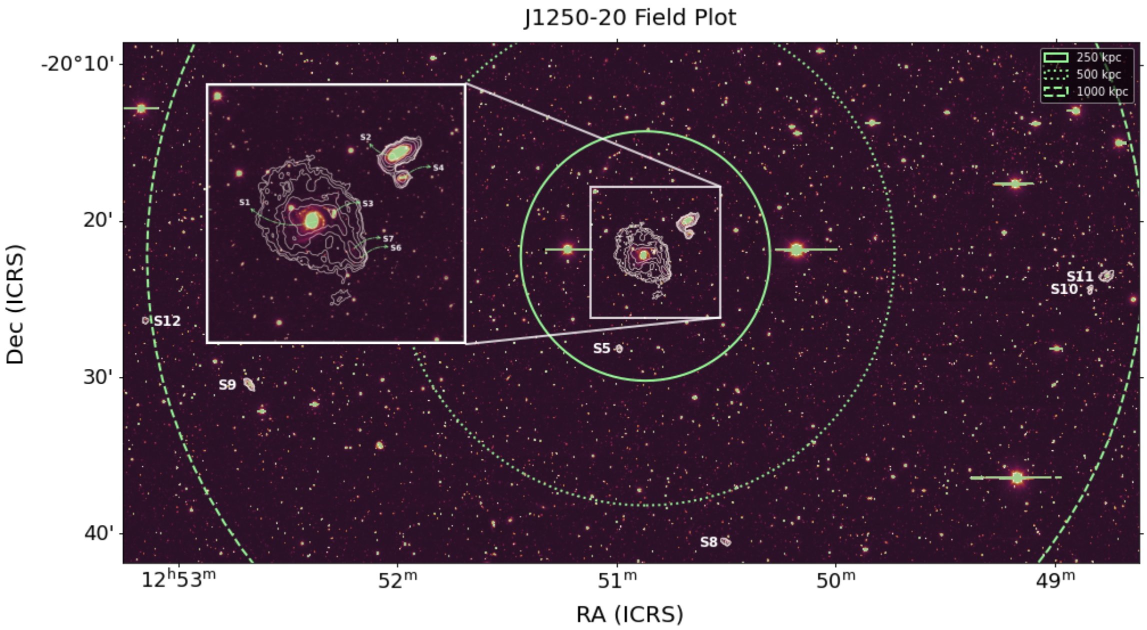

Figure 1. DECam g band image of MeerKAT's 1 degree field centered at J1250-20 S1. The green circles correspond to 250, 500, and 1000 kpc projected distance from the center of the field. The inset highlights galaxies S1, S2, S3, S4, and Hα emitters S7 and S6.

J1250 was observed with MeerKAT in L-band with the 32k correlator mode in late February and April 2021 as part of the 2020 Open Time Proposal, MKT-20172 (PI: Moses Mogotsi). The full track of 4.78 hours was split into two blocks, a rising block and a setting block, to ensure efficient scheduling and to increase the uv coverage. The radio bright QSO *B1245-197*, $\sim 42'$ offset from the phase centre contaminates the field by inducing artefacts and disproportionately increasing the noise. The channels affected by strong RFI attributed to GPS L3 are ignored while imaging. After both the blocks have been observed, the two visibility sets from the correlator are fed to the SARAO SDP calibration pipeline individually. The pipeline flags RFI signals, computes various calibration solutions (flux, phase, gain, bandpass) and applies the corrections to the data. We utilize the CASA[14] task tclean for continuum and spectral line imaging, SoFiA2[15] for producing clean-masks, CARTA[16] and SoFiA-Image-Pipeline[17] for inspection. The continuum of 15 MHz chunks centered at the redshifted HI emission extracted from the resulting gain-corrected, bandpass, and flux calibrated Measurement Sets (L1 visibility) are modelled and subtracted independently before being concatenated. This was to ensure optimal subtraction of the artefacts induced by the bright sources in the field. The final concatenated MS is imaged to produce $12''$ ($11.74'' \times 10.68''$, $-14.07\,^{\circ}$) and $16''$ ($16.15'' \times 16.09''$, $54.25\,^{\circ}$) cubes with the latter being used for kinematic analysis. The final cubes with an RMS of $\sim$ 0.2mJy, which is 10 times lower than that of the ATCA cube, detect HI down to a column density of $\sim 3 \times 10^{19}\,\mathrm{cm}^{-2}$. The MeerKAT cubes apart from having a smaller, more uniform beam also have a spectral resolution of $5.5\ \mathrm{km\,s}^{-1}$, which is ~ 3 times higher than the ATCA cube. In MeerKAT's $\sim 1°$ field-of-view (~ 1.9 Mpc; see figure 1), we detect HI in 5 other dwarf galaxies with optical counterparts in the deep DECam images (S8 - S12), which we denote as potential group members. Only S11 (2MASS J12484609-2023346) was reported in Dz21[12]. S9 (2MASS J12524037-2030315 or LEDA 840758) does not have a redshift in the literature and the other three (S8, S10, S12) have not yet been identified as sources let alone dwarf galaxies. We recover an HI mass for S1 and S2 of $M_{HI}[M_\odot] = 10.56 \pm 0.01$ for a group distance of ~ 117 Mpc, consistent with previously reported masses. The distance is the luminosity distance at the systemic velocity obtained from kinematic modelling.

2.2. Gas Kinematics in S1

We perform 3D tilted ring modelling using ^{3D}BAROLO [18] to extract the kinematic and geometric parameters of the neutral gas envelope of S1. In panel (d) of figure 2, we compare three 7-ring models of the disc: (I) Receding side, (II) Approaching side, and (III) Both sides. We also perform Gaussian decomposition to study the component structure and to separate planar gas, extraplanar gas, and gas associated with S3. We utilize the machine learning assisted automated fitting tool, Gausspy+ [19] to decompose the spectra along each spaxel into either single or multiple Gaussian components. To avoid over-fitting and un-physical components we specify a maximum of 3 components per spaxel. The use of the corrected Akaike Information Criterion (AICc) for model selection also ensures that the model with the least number of components has a higher propensity for being selected. The fitting also takes into account spatial coherence due to the beam as well as the physical distribution of gas. The recovered component map and some fitted spectra is shown in panel (a) of figure 2.

The HI disc of S1 is extended, asymmetric, warped, and lopsided. Most of the rotating gas associated with S3 is distinctly seen in the component structure as additional components. We see indications of EPG near the center, S3, and along the SE stellar stream. We also see an HI plume SW of the SE stellar stream. Within the resolution of our data, we do not see any distinct kinematic signatures associated with the Hα emitters, S7 and S6. From the kinematics, it is evident that the HI disc is affected by the interaction between S1 and S3. S1's interactions with S2 and S4 could also be contributing to the observed gas distribution. Although, the resolved and uniformly sampled MeerKAT data reveals the absence of a significant tidal bridge connecting S1, S4, and S2, contrary to the ATCA data (Dz19[11]). However, two observations lend credence to the argument of a low column density interaction between S1, S2, and S4. Firstly, the velocity centroids in the SE stellar stream, the approaching side of S4, and the receding side of S2 appear to be comparable. Secondly, the kinematic center of the gas envelope of S4 seem to be offset from the optical center in the SW direction, the direction corresponding to S1. The kinematic offset in S4 is not surprising given its proximity to and clear interaction with S2, but the direction of the offset bolsters the scenario of another low column density interaction with S1. Since the interactions are mostly confined to the receding side, we model both sides independently to attempt to isolate the influence of these interactions on the extended disc. For the PVD (panel (c) of figure 2), we overlay the contours (green) of the 7-ring model of the approaching side (NW) of the disc. From the model we recover an average position angle of $252\,°$ measured from N to receding side. The P.A extracted from R-band data in the SINGG catalog was $\sim 304\,°$. The inclination obtained from the tilted ring modeling of both sides is $\sim 39.5\,°$ and that obtained from the other two models vary by $\sim 1\,°$ on either end. We recover a falling rotation curve from all three of our models of the warped disc. The slow rotating extended gas on the receding side also shows up as beard gas in the PVD.

3. Conclusion

In this era of high sensitivity, spatially resolved spectroscopy facilitated by modern day interferometers and integral field spectrographs, we can now study resolved kinematics and

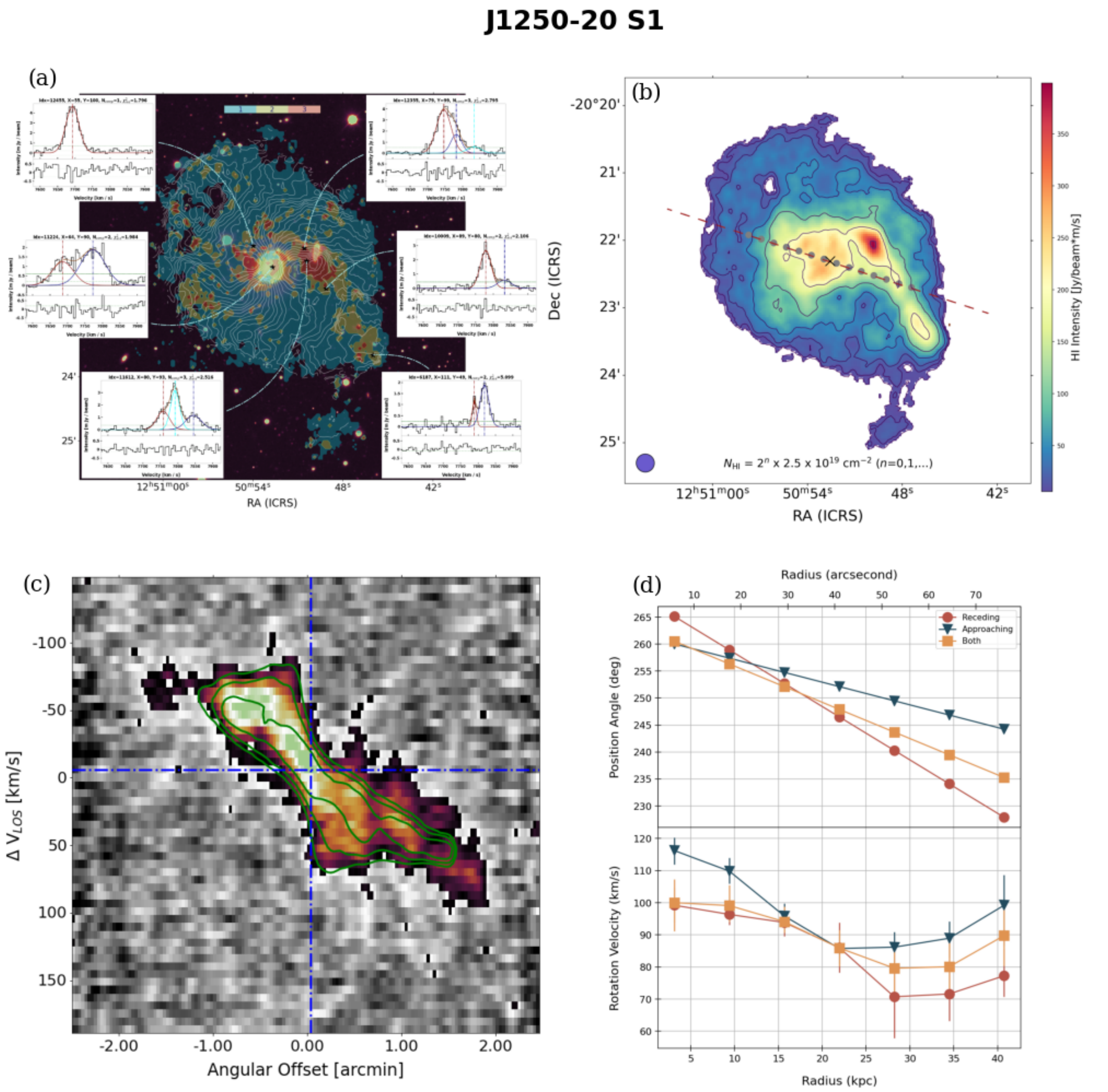

Figure 2. The moment maps and component fits are from the 16″ cube and the PVD is from the 12″ cube. Panel **(a):** HI moment 1 contours and map of the number of fitted Gaussian components overplotted on DECam g band image. The plot also shows the spectrum of some select voxels fitted with either single or multiple Gaussian components. Panel **(b):** Moment 0 map of the HI envelope of S1 above a column density of $3.2 \times 10^{19}\,\mathrm{cm}^{-2}$. The circular show the position of the 7 rings used for tilted ring modelling. The brown dashed line indicates the slice along which the PVD on the next panel was extracted. Panel **(c):** S1 major axis PVD extracted along a length of 5′ with a width of 3′ roughly spanning the minor axis. The green contours denote the model obtained from 7 ring tilted ring modelling of the approaching side (NW on sky; top of the PVD). The slice was extracted with a position angle of 252°, the average P.A of the model. Panel **(d):** Comparison of P.A and rotation velocity obtained from the 7 ring modelling of the receding side (SE), approaching side (NW), and both sides.

disc dynamics of multi-phase gas in galaxies residing in various environments. Our preliminary analysis of the neutral gas kinematics of a low-inclination, late-type galaxy with ongoing minor and major interactions in a group reveal a warped, lopsided, and asymmetric disc with extensive extra-planar gas, an HI plume, slow rotating extended gas, and possible deviations from circular motion. In a future work, we will report the detailed gas kinematics of all of the group members along with an evaluation of galaxies in the extended field.

References

[1] Sancisi R, Fraternali F, Oosterloo T and van der Hulst T 2008 *The Astronomy and Astrophysics Review, Volume 15, Issue 3, pp.189-223* **15** 189 ISSN 0935-4956

[2] de Blok W J G, Walter F, Brinks E, Trachternach C, Oh S H and Kennicutt R C 2008 *The Astronomical Journal* **136** 2648–2719 ISSN 0004-6256, 1538-3881

[3] Zschaechner L K, Rand R J, Heald G H, Gentile G and Kamphuis P 2011 *The Astrophysical Journal* **740** 35 ISSN 0004-637X

[4] Boomsma R, Oosterloo T A, Fraternali F, van der Hulst J M and Sancisi R 2008 *Astronomy and Astrophysics, Volume 490, Issue 2, 2008, pp.555-570* **490** 555 ISSN 0004-6361

[5] Marasco A, Fraternali F, Heald G, de Blok W J G, Oosterloo T, Kamphuis P, Józsa G I G, Vargas C J, Winkel B, Walterbos R a M, Dettmar R J and Jütte E 2019 *Astronomy & Astrophysics, Volume 631, id.A50, 27 pp.* **631** A50 ISSN 0004-6361

[6] Marasco A and Fraternali F 2011 *Astronomy and Astrophysics* **525** A134 ISSN 0004-6361

[7] Sweet S M, Meurer G, Drinkwater M J, Kilborn V, Dénes H, Bekki K, Hanish D, Ferguson H, Knezek P, Bland-Hawthorn J, Dopita M, Doyle-Pegg M T, Elson E, Freeman K, Heckman T, Kennicutt R, Kim J H, Koribalski B, Meyer M, Putman M, Ryan-Weber E, Smith C, Staveley-Smith L, Wong O I, Webster R, Werk J and Zwaan M 2013 *Monthly Notices of the Royal Astronomical Society* **433** 543–559 ISSN 0035-8711

[8] Meurer G R, Hanish D J, Ferguson H C, Knezek P M, Kilborn V A, Putman M E, Smith R C, Koribalski B, Meyer M, Oey M S, Ryan-Weber E V, Zwaan M A, Heckman T M, Kennicutt Jr R C, Lee J C, Webster R L, Bland-Hawthorn J, Dopita M A, Freeman K C, Doyle M T, Drinkwater M J, Staveley-Smith L and Werk J 2006 *The Astrophysical Journal Supplement Series* **165** 307–337 ISSN 0067-0049

[9] Hanish D J, Meurer G R, Ferguson H C, Zwaan M A, Heckman T M, Staveley-Smith L, Bland-Hawthorn J, Kilborn V A, Koribalski B S, Putman M E, Ryan-Weber E V, Oey M S, Kennicutt Jr R C, Knezek P M, Meyer M J, Smith R C, Webster R L, Dopita M A, Doyle M T, Drinkwater M J, Freeman K C and Werk J K 2006 *The Astrophysical Journal* **649** 150–162 ISSN 0004-637X

[10] Meyer M J, Zwaan M A, Webster R L, Staveley-Smith L, Ryan-Weber E, Drinkwater M J, Barnes D G, Howlett M, Kilborn V A, Stevens J, Waugh M, Pierce M J, Bhathal R, de Blok W J G, Disney M J, Ekers R D, Freeman K C, Garcia D A, Gibson B K, Harnett J, Henning P A, Jerjen H, Kesteven M J, Knezek P M, Koribalski B S, Mader S, Marquarding M, Minchin R F, O'Brien J, Oosterloo T, Price R M, Putman M E, Ryder S D, Sadler E M, Stewart I M, Stootman F and Wright A E 2004 *Monthly Notices of the Royal Astronomical Society* **350** 1195–1209 ISSN 0035-8711

[11] Džudžar R, Kilborn V, Meurer G, Sweet S M, Drinkwater M, Bekki K, Audcent-Ross F, Koribalski B, Kim J H, Putman M, Ryan-Weber E, Zwaan M, Bland-Hawthorn J, Dopita M, Doyle-Pegg M T, Elson E, Freeman K, Hanish D, Heckman T, Kennicutt R, Knezek P, Meyer M, Smith C, Staveley-Smith L, Webster R and Werk J 2019 *Monthly Notices of the Royal Astronomical Society* **483** 5409–5425 ISSN 0035-8711

[12] Džudžar R, Kilborn V, Sweet S M, Meurer G, Jarrett T H and Kleiner D 2021 *Monthly Notices of the Royal Astronomical Society* **500** 3689–3710 ISSN 0035-8711

[13] Kleiner D, Pimbblet K A, Jones D H, Koribalski B S and Serra P 2017 *Monthly Notices of the Royal Astronomical Society* **466** 4692–4710 ISSN 0035-8711

[14] McMullin J P, Waters B, Schiebel D, Young W and Golap K 2007 **376** 127

[15] Westmeier T, Kitaeff S, Pallot D, Serra P, van der Hulst J M, Jurek R J, Elagali A, For B Q, Kleiner D, Koribalski B S, Lee-Waddell K, Mould J R, Reynolds T N, Rhee J and Staveley-Smith L 2021 *Monthly Notices of the Royal Astronomical Society* **506** 3962–3976 ISSN 0035-8711

[16] Comrie A, Wang K S, Hsu S C, Moraghan A, Harris P, Pang Q, Pińska A, Chiang C C, Chang T H, Hwang Y H, Jan H, Lin M Y and Simmonds R 2021 CARTA: The Cube Analysis and Rendering Tool for Astronomy Zenodo

[17] Hess K M, paoloserra, Boschman L, Shen A and H J 2022 Kmhess/SoFiA-image-pipeline: SoFiA Image Pipeline v1.2.0 Zenodo

[18] Di Teodoro E M and Fraternali F 2015 *Monthly Notices of the Royal Astronomical Society* **451** 3021–3033 ISSN 0035-8711

[19] Riener M, Kainulainen J, Beuther H, Henshaw J D, Orkisz J H and Wang Y 2020 *Astronomy & Astrophysics, Volume 633, id.A14, 25 pp.* **633** A14 ISSN 0004-6361