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Environmental processes at work in galaxy clusters: triggering of the AGN activity and development of X–ray tails

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Abstract. We exploited the archival *Chandra* data to explore the connection between the X-ray emission and the ram–pressure stripping phenomenon in cluster galaxies extracted from the GASP survey. The X-ray analysis, coupled with the MIR-WISE colors, confirms the presence of AGNs at the center of galaxies with AGN-like optical line ratios. For the other candidate ram–pressure stripped galaxies with X-rays counterparts, the most likely interpretation is the presence of an obscured AGN with extended X-ray emission. Furthermore, for the galaxies that could benefit from long *Chandra* exposure times, a clearly X-rays emitting tail has been detected, suggesting a complex interplay between the galaxy ISM and the surrounding ICM. The hot plasma responsible for the extended emission is most likely responsible both for the X-ray emission and for the [OI]/Hα excess found from the analysis of the optical line ratios. Our analysis of the magnetic fields in the tail of JO206 suggests this could be a direct consequence of the ICM draping and demonstrates the extremely powerful capabilities of joint multiwavelength datasets.

Key words. Galaxies: clusters: general – Galaxies: Seyfert – X-rays: galaxies

1. Introduction

It is widely accepted that there is a strong connection between the presence of an Active Galactic Nucleus (AGN) and the host galaxy properties (Heckman & Best 2014, for a recent review), while the way this interaction occurs is much less clear, and it may involve a range of different physical processes (mergers, bars among others). Among the unresolved issues concerning AGNs in galaxies is the connection between AGNs and environment in which their host galaxies live. Optically-based studies (Dressler et al. 1985; Marziani et al. 2017) suggest that the fraction of AGN in clusters (∼1-3%) is significantly lower than that in the field (∼5-8%), while studies based on X-ray data find instead a comparable fraction (Pimbblet et al. 2013).

The GASP (GAs Stripping Phenomena in Galaxies) survey is aimed at studying the gas removal processes in cluster galaxies by means of IFU MUSE observations (Poggianti et al. 2017b). This survey has recently demonstrated that, unexpectedly, 6 out of 7 galaxies undergoing strong ram pressure stripping (RPS), host an AGN (Poggianti et al. 2017a; Radovich et al. 2019), suggesting a link between these two phenomena. These results favor a scenario in which RPS is able to convey the gas toward the galaxy center, triggering the AGN activity.

In Peluso et al. (2021) we performed a complete census of AGN activity in stripped galaxies in clusters using both GASP and literature data to increase the overall statistics. In particular, we compared the AGN fraction in our GASP sample (white arrow in Fig.1) and in the extended literature sample (ALL-RPS, grey arrow in Fig.1) with the fraction of AGN in a sample of field galaxies from the MaNGA (Mapping Nearby Galaxies at Apache Point Observatory, Bundy (2014)) survey having the same mass distribution (red distributions in Fig.1) of the RPS sample. We found that indeed RPS galaxies host a significant population of AGNs (27% and 51% in galaxies with masses above 10^9 and 10^{10} solar masses, respectively).

However, this study is based on the optical detection of AGNs, while it is well known that some of them are only visible at X-ray, but not at optical wavelengths. As an example, in our GASP JO36 galaxy the AGN is not seen in MUSE, but is detected by *Chandra* (Fritz et al. 2017). X-ray data are therefore crucial to have a complete AGN census and draw definitive conclusions regarding the connection between AGN presence and ram pressure stripping.

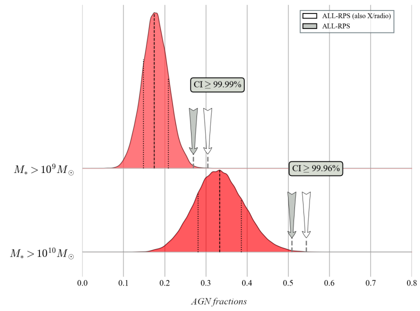

Fig. 1. AGN fraction in ram-pressure stripped galaxies (white arrow: GASP, grey arrow: GASP and literature) compared to the AGN fraction in field galaxies from MaNGA (red distributions) with the same mass distribution: upper plot refer to the fraction in galaxies above $10^9 M_\odot$ and lower plot to galaxies above $10^{10} M_\odot$.

In this project we aim at using the archival *Chandra* data to search for AGNs in all the GASP galaxies and all galaxies in the GASP clusters. In doing this, we also reveal the presence, if any, of X-rays emitting tails of hot gas departing from spiral galaxies, which are believed to be due to the mixing of the stripped cold Inter Stellar Medium (ISM) with the hot cluster Intra Cluster Medium (ICM). Only very few such cases were known so far (e.g. Sun et al. 2010, 2021; Laudari et al. 2021).

2. AGNs in *Chandra*

In order to probe the possible connection between the ram-pressure stripping and the presence of an AGN in cluster galaxies we took advantage of the existence of both X–rays and infrared databases to analyze the entire Poggianti et al. (2016) sample. This includes also the galaxies observed within the GASP survey, where the optical line ratios could be spatially resolved. For the matched galaxies without the MUSE counterpart, we took advantage, when possible, of the existing fiber spectra from WINGS/OmegaWINGS (Moretti et al. 2017).

We first matched the Poggianti et al. (2016) catalog of candidate RPS galaxies with the

Chandra Source Catalog CSC 2.0.1 using a matching radius of 5 arcsec. We found 14/344 RPS candidates associated with X-ray point sources (see Tab. 1). The X-ray counts were derived using a background that includes the cluster contribution at the position of the galaxy following the method described in Poggianti et al. (2019) and Campitiello et al. (2021).

We then downloaded *Chandra* X-ray Observatory observations of our targets from *Chandra* data archive, taken with the Advanced CCD Imaging Spectrometer (ACIS) detector. The reprocessed images clearly reveal AGN–like pointed X-ray emission at the center of the candidate jellyfish galaxies (Moretti+, in prep). For some galaxies (JO194, JO85, JW38, JW76) the hard X-rays emission is very faint, while the emission in the soft band is clearly seen. Two galaxies (JW3, also in Fig. 2 and JW73) show a secondary source close to the galaxy center mostly visible in the hard band, that is somewhat reminiscent of the candidate Ultra Luminous X-ray source (ULX) found in the stripped tail of JW100 (Poggianti et al. 2019). The secondary source can also be seen in the optical (see the catalog published in Poggianti et al. 2016). Among the matched galaxies some are also part of the GASP survey (9/54), and therefore possess a MUSE observation that has allowed us to classify them as real jellyfish galaxies (see Bellhouse et al. 2017; Poggianti et al. 2017b, 2019). Interestingly enough, among these galaxies the ones with long integration time (JO201, JW100 and also JO194) show galactic X-ray diffuse emission in 0.5 - 2 keV band.

We then extracted the X-ray spectra of the central 3″region for the sources with at least 70 net counts in the full energy band (5 sources, listed at the top of Tab.1), to ensure at least 15 counts in each final spectral bin.

As local background we used the emission from an annulus whose inner radius is 5 arcsec and outer radius is 7 arcsec (see Fig.2). The task `specextract` was employed to extract the energy spectra, which were grouped to have at least 15 counts in each spectral bin and fitted in XSPEC 12.10.1f (Arnaud 1996), making different assumptions. We find that the

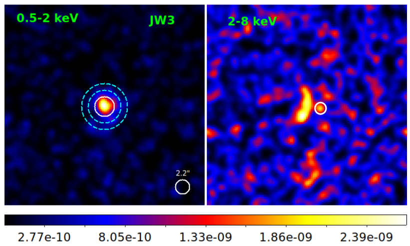

Fig. 2. Soft and hard X-rays images of the galaxy JW3. The white circle on the right panel shows a secondary source.

spectra of JO206, JO36, JW100, JW103, and JW3 have a better fit when N_H is more than one fold to the Galactic value, indicating potential intrinsic absorption.

For the sources with only a marginal detection, possibly due to the lower integration time, we used the `srcflux` tool to calculate count rates in the broad (0.5-8 keV) energy band. These counts in the broad energy band were then converted to unabsorbed fluxes using the Portable, Interactive Multi-Mission Simulator (PIMMS). We assumed the underlying spectrum to be a power law with Γ = 1.7, typical for AGNs in nearby galaxies (Ho 2008; Wang et al. 2016) and a Galactic absorption (Kalberla et al. 2005). We then used different assumptions on the intrinsic galaxy absorption to derive the possible X-rays luminosities, that are in agreement with an AGN emission only assuming a very high degree of obscuration (N_H=10^{23} cm^{-2}).

Mid-infrared WISE photometry provides an effective way to select dusty AGN. In particular, AGNs are traced by red (> 0.75) W1-W2 colors; however, as discussed by Stern et al. (2012), if dust extinction is high, E(B-V) >> 1, the mid-infrared emission from the AGN is more and more diluted by the host galaxy contribution and hence bluer W1-W2 (∼ 0.5) colors are expected. Candidate jellyfish galaxies from Poggianti et al. (2016) have been matched with the Allwise catalog (Cutri et al. 2021) using a radius of 5 arcsec, finding a match for 334 sources. All the matched sources are shown in

Galaxy	*Chandra* ID	Significance	redshift	RA	DEC	N_H (cm^{-2})	S (0.5-2 keV)	H (2-8 keV)
JO206	2CXO J211347.3+022834	23.08	0.051	318.44754	2.4765272	5.28×10^{20}	60.48±7.81	421.60±20.54
JO194	2CXO J235700.7-344050	13.30	0.042	359.253082	-34.680538	1.10×10^{20}	127.36±11.57	11.09±4.36
JO201	2CXO J004130.3-091546	12.83	0.045	10.3762293	-9.2627726	2.73×10^{20}	238.22±15.68	42.76±7.0
JW100	2CXO J233625.0+210902	10.79	0.062	354.1043932	21.1507345	3.85×10^{20}	183.67±15.20	117.75±11.66
JW3	2CXO J010317.2-214445	5.88	0.053	15.8219828	-21.7460609	1.55×10^{20}	56.80±7.85	19.29±5.23
JO36	2CXO J011259.4+153529	5.35	0.040	18.2475208	15.5915518	3.85×10^{20}	7.19±2.82	18.07±4.35
JO85	2CXO J232431.3+165205	5.22	0.036	351.1308813	16.8683152	2.98×10^{20}	10.18±3.31	0.36±1.41
JW73	2CXO J135939.2+280340	4.06	0.036	209.9140246	28.0612205	1.23×10^{20}	10.87±3.31	6.85±2.64
JO135	2CXO J125704.2-302229	4.00	0.054	194.2680071	-30.3750537	6.24×10^{20}	14.37±3.87	5.50±2.45
JW103	2CXO J233626.5+211054	3.95	0.062	354.1106196	21.1818416	3.83×10^{20}	10.10±7.41	3.78±4.02
JW39	2CXO J130407.8+191239	2.86	0.066	196.0321635	19.2106686	2.11×10^{20}	4.72±2.23	1.51±1.41
JW76	2CXO J154522.4+360533	2.54	0.063	236.3440003	36.0924146	1.62×10^{20}	8.58±3.00	1.55±1.42
JW38	2CXO J130352.4+191600	2.11	0.065	195.9678339	19.2670075	2.19×10^{20}	10.50±3.61	0.13±1.00
JW64	2CXO J134917.6+264504	1.64	0.065	207.3224068	26.7515458	1.01×10^{20}	14.03±5.19	4.41±4.80

Table 1. Properties of sources detected at JF galaxy location. Columns are (1) galaxy name (2) *Chandra* Id (3) significance (4) redshift (5)&(6) J2000 position (7) Galactic neutral hydrogen column density (8) net counts with errors in the S (0.5 - 2 keV) band (9) net counts with errors in the H (2 - 8 keV) band with errors.

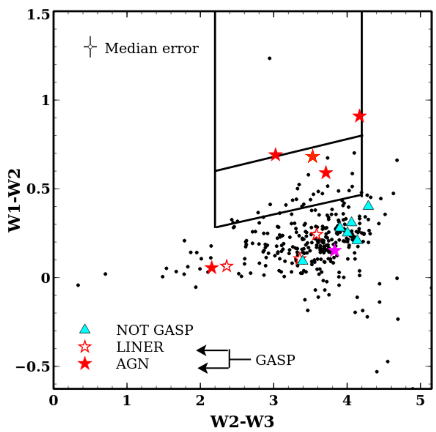

Fig. 3. WISE W1-W2 vs. W2-W3 diagram for RPS candidates from Poggianti et al. (2016) shown by black symbols. Stars mark sources that are part of the GASP survey and have been classified as AGN (red filled), LINER (red empty) or Composite (magenta filled) according the the optical diagnostic diagram. Cyan triangles are galaxies with X–rays emission lacking the optical IFU data from GASP. The black continuous line shows the 'WISE AGN' region defined by Jarrett et al. (2011) and its extension to bluer (W1-W2) colors described in (Weston et al. 2017)

Fig. 3 as black dots. Errors on the WISE magnitudes range from 0.025 in W1 and W2, to 0.07 in W3.

The Jarrett et al. (2011) "wedge" is shown in Fig. 3, with a black continuous line box, and shows the region where matched sources have a higher probability to be AGN. The "extended" AGN region by Weston et al. (2017) is also shown in Fig. 3, as an extension of the original one to bluer (W1-W2) colors to include more highly obscured AGN, at the cost of a larger contamination from star-forming galaxies. We find that of the GASP galaxies for which the MUSE optical line ratios have demonstrated the presence of an AGN (Poggianti et al. 2017a; Radovich et al. 2019), two (JO135, JO206) fall in the original AGN wedge region; other two (JO204, JO201) are in the extended region, where other candidate ram-pressure stripped galaxies are also located. In the latter case, however, there is no information from X–rays, nor from the optical IFU data that we possess to clearly characterize them as active galaxies.

3. X-rays tails

While the physics of RPS galaxies disks has now received a great deal of interest, with GASP being the first statistical sample studied so far, the high-energy side of jellyfish galaxies tails is still deeply unexplored. In fact, only a few objects have been studied in detail: ESO 137-001 and ESO 137-002 in A3627 (Sun et al. 2010; Zhang et al. 2013; Laudari et al. 2021) and the GASP galaxies JW100 in A2626 (Poggianti et al. 2019) being the best studied so far. In all the RPS galaxies with X-rays tails, it

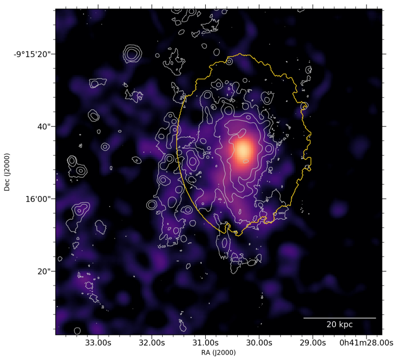

Fig. 4. X-ray emission in JO201: white contours represent the Hα emission, while the gold contour represents the stellar disk region.

has been found that the extended X-ray emission is produced by a hot plasma with a temperature in the range kT=0.7–1 keV, likely originating from the interplay between the ISM and the ICM on the surface of the stripped tails. The X-ray emitting plasma would then result from the ICM–ISM interaction triggered by the stripping, which causes either the heating of the ISM through shocks and conduction, or the cooling of the ICM onto the galaxy or the ICM–ISM mixing. In our search for high energy sources in X-rays archival data, we found two interesting objects (JO201 and JO194) with a gaseous tail clearly emitting in X-rays. While data on JO194 are still under investigation, the analysis on JO201 has already been published in Campitiello et al. (2021) (see also Fig.4). By means of the analysis of ~ 187 kiloseconds of *Chandra* archival data, coupled with the GASP MUSE data, we found that the X-ray luminosity of the galaxy is provided by two contributions: the AGN emission (with a Γ = 1.7 and very high absorption column, typical of a Compton thick source, i.e. of the order of N_H=10^{24} cm^{-2}) and an extended contribution. This last emission is provided by an extended source associated with a hot plasma (kT$\approx$1 keV) whose X-ray luminosity is one order of magnitude higher than the X-ray luminosity expected from the Star Formation only. The correlation between the Hα and X-ray surface brightness emerging from the point-to-point analysis reveals that this galactic X-ray emitting plasma closely follows the spatial distribution of the ISM.

This hot galactic plasma is probably responsible for both the X-ray emission and the [OI]/Hα excess derived from the MUSE optical emission lines. Furthermore, our CLOUDY (Ferland et al. 2017) simulations seem to suggest a low metallicity of the ionizing plasma indicating that the origin of the hot plasma is strictly connected to the ICM itself. This suggests that the nature of the interaction between the ICM and the ISM is either the cooling of the ICM or the mixing of these two plasmas. On the basis of the results obtained from the radio study of the jellyfish galaxies JO206 and JW100 (Müller et al. 2021b,a; Ignesti et al. 2021), we speculate that this process could be a direct consequence of the ICM draping (Sparre et al. 2020) and thus that joint radio and X-ray analyses can provide complementary insights on this mechanism.

4. Conclusions

Our *Chandra* archival search of RPS cluster galaxies showing evidence of X-rays emission has confirmed that the presence of a central AGN is clearly detected only in galaxies that have long tails of stripped gas. In these galaxies the optical line ratios strongly favor the AGN origin for the ionized gas emission. There is still, however, a population of galaxies where both optical line ratios and X-rays emission are not giving conclusive results. Our interpretation, also based on the galaxies infrared colors, favors the presence of a highly obscured AGN.

RPS galaxies that have long *Chandra* exposure times also show X-rays emitting tails, whose position is very similar to the ionized gas emission hinting toward a common origin. Our analysis (Poggianti et al. 2019; Campitiello et al. 2021) suggests indeed that RPS galaxies are surrounded by a hot plasma that is responsible both for the X-ray emission and for the peculiar optical line ratios found along the tails. The presence of polarized non-thermal radio emission following the tail extension in JO206 suggests the presence of ICM draping. This ordered magnetic field may prevent heat and momentum exchange, and favour in situ star formation in the tail (Müller et al. 2021b). The new ongoing *Chandra* observations of the JO206 tail (P.I. A. Ignesti, 220 ks), aimed at confirming the presence of extended X-ray emission in JO206 would prove that X-ray and ordered fields can be produced by the same process, thus deepening our knowledge of the outcomes of ram pressure stripping.

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References

Arnaud, K. A. 1996, in Astronomical Society of the Pacific Conference Series, Vol. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes, 17
Bellhouse, C., Jaffé, Y. L., Hau, G. K. T., et al. 2017, The Astrophysical Journal, 844, 49
Bundy, K. 2014, Proceedings of the International Astronomical Union, 10, 100
Campitiello, M. G., Ignesti, A., Gitti, M., et al. 2021, The Astrophysical Journal, 911
Cutri, R. M., Wright, E. L., Conrow, T., et al. 2021, VizieR Online Data Catalog: AllWISE Data Release
Dressler, A., Thompson, I. B., & Shectman, S. A. 1985, The Astrophysical Journal, 288, 481
Ferland, G. J., Chatzikos, M., Guzmán, F., et al. 2017, 53, 385
Fritz, J., Moretti, A., Gullieuszik, M., et al. 2017, Astrophysical Journal, 848, 132
Heckman, T. M. & Best, P. N. 2014, Annual Review of Astronomy and Astrophysics, 52, 589
Ho, L. C. 2008, Annual Review of Astronomy and Astrophysics, 46, 475
Ignesti, A., Vulcani, B., Poggianti, B. M., et al. 2021, arXiv e-prints, arXiv:2110.12719
Jarrett, T. H., Cohen, M., Masci, F., et al. 2011, The Astrophysical Journal, 735, 112
Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, Astronomy & Astrophysics, 440, 775
Laudari, S., Jáchym, P., Sun, M., et al. 2021, Monthly Notices of the Royal Astronomical Society, 509, 3938
Marziani, P., D'Onofrio, M., Bettoni, D., et al. 2017, Astronomy & Astrophysics, 599, A83
Moretti, A., Gullieuszik, M., Poggianti, B., et al. 2017, Astronomy & Astrophysics, Volume 599, id.A81, 11 pp., 599
Müller, A., Ignesti, A., Poggianti, B., et al. 2021a, Galaxies, 9, 116
Müller, A., Poggianti, B. M., Pfrommer, C., et al. 2021b, Nature Astronomy, 5, 159
Peluso, G., Vulcani, B., Poggianti, B. M., et al. 2021, arXiv e-prints, arXiv:2111.02538
Pimbblet, K. A., Shabala, S. S., Haines, C. P., Fraser-McKelvie, A., & Floyd, D. J. E. 2013, Monthly Notices of the Royal Astronomical Society, 429, 1827
Poggianti, B. M., Fasano, G., Omizzolo, A., et al. 2016, Astronomical Journal, 151
Poggianti, B. M., Ignesti, A., Gitti, M., et al. 2019, The Astrophysical Journal, 887, 155
Poggianti, B. M., Jaffé, Y. L., Moretti, A., et al. 2017a, Nature, 548, 304
Poggianti, B. M., Moretti, A., Gullieuszik, M., et al. 2017b, The Astrophysical Journal, 844, 48
Radovich, M., Poggianti, B., Jaffé, Y. L., et al. 2019, Monthly Notices of the Royal Astronomical Society, 486, 486
Sparre, M., Pfrommer, C., & Ehlert, K. 2020, Monthly Notices of the Royal Astronomical Society, 499
Stern, D., Assef, R. J., Benford, D. J., et al. 2012, The Astrophysical Journal, 753, 30
Sun, M., Donahue, M., Roediger, E., et al. 2010, The Astrophysical Journal, 708, 946
Sun, M., Ge, C., Luo, R., et al. 2021, Nature Astronomy
Wang, S., Liu, J., Qiu, Y., et al. 2016, The Astrophysical Journal Supplement Series, 224, 40
Weston, M. E., McIntosh, D. H., Brodwin, M., et al. 2017, Monthly Notices of the Royal Astronomical Society, 464, 3882
Zhang, B., Sun, M., Ji, L., et al. 2013, The Astrophysical Journal, 777, 122