Is the Milky Way Unique?

Characterizing the X-Ray Properties of Milky Way Analogs in the SAGA Catalog

by

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Is the Milky Way Unique: Characterizing the X-Ray Properties of Milky Way Analogs in the SAGA Catalog

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ABSTRACT

We present 18 Milky Way-like galaxies from the Satellites Around Galactic Analogs (SAGA) catalog that have active X-ray activities at the galactic center. With X-ray data from Chandra Observatory, these black holes have observed luminosities $L_{2-10leV} \sim 10^{38} - 10^{41} erg \cdot s^{-1}$. Using additional information of far-UV from Galaxy Evolution Explorer (GALEX) and infrared from Wide-field Infrared Survey Explorer (WISE), we calculate the star formation rate (SFR) for each galaxy and estimate its expected X-ray luminosity from XRBS $L_{2-10leV}(XRB) \sim 10^{37} - 10^{40} erg \cdot s^{-1}$. The high agreement between the observed and expected X-ray luminosity indicates the existence of XRBs in our selected candidates at the galactic center. Follow-up observation and analysis with other data archives can extend this relationship to a larger sample of galaxies.

Keywords: galaxies: evolution – X-ray: galaxies – X-ray: binaries

1. INTRODUCTION

The Milky Way is a spiral galaxy with a visible diameter of over 100000 light-years. It contains hundreds of billions of stars, one of which is our Sun. The galactic center hosts an intense radio source, Sagittarius A*, and supermassive black holes (SMBHs) of 4.1–4.5 million solar masses (Ghez et al. 2008), but it is not active. In an active galaxy, dust and gas constantly fall into the black hole and glow brightly. The Milky Way is not doing this, and any material not directly falling into the black hole will stays. Hence we cannot see anything around the black hole.

The Milky Way is unusual, for it hosts the only known star on which life survives. Given its brightness and mass, it is rare for our galaxy to have two bright and nearby satellites, the Large and Small Magellanic Clouds (Liu et al. 2011). On the other hand, the Milky Way is nowhere close to being unique since numerous galaxies in the universe assemble the Milky Way in many ways, such as mass, size, shape, and rotational velocity. With a large base, even a small percentage of positive matches indicates plenty of Milky Way-like galaxies.

It is now well-established that massive black holes (BHs) reside in the nuclei of every giant galaxy with a bulge (Kormendy & Ho 2013). It includes many Milky Way analogs. However, whether these galaxies are active or quenched raises an interesting question. An active galaxy holds an active galactic nucleus (AGN), a compact region at the center with a much higher-than-normal luminosity. As pointed out, the Milky Way is not active. For the Milky Way analogs, we can deduce their properties by observing their X-ray luminosities.

This paper explores the X-ray property of some Milky Way analogs using archival data from the Chandra X-ray Observatory (Evans et al. 2010). With its precise measurement of hard band energy flux and ability to resolve X-ray point sources, Chandra gives a wealth of information on accretion signatures from massive BHs. We then compare the observed X-ray luminosity with the expected X-ray luminosity due to X-ray binaries (XRB) and use this information to determine the sources of X-rays in the galaxies.

2. SAMPLE SELECTION

Throughout the process of sample selection, we need various information from different sources. However, there are often very few overlaps between these catalogs, forcing us to further restrict our candidates to those present in all of them. To investigate the properties of the Milky Way analog, the first step is to search for candidates that are similar to Milky Way. Satellites Around Galactic Analogs (SAGA) catalog (Mao et al. 2021) provides one of the best resources for this purpose. In the stage II survey, SAGA identifies around 100 Milky Way analogs at $z \sim 0.01$. In the most updated form, it has 300 host galaxies that highly assemble the Milky Way. This catalog provides helpful information that characterizes the host galaxies, such as locations, distances, masses, star densities, etc. However, it lacks the X-ray properties that we seek in this paper. Chandra Data Archive gives a solution. Chandra provides the most complete and the most advanced survey of galaxies in the X-ray spectrum, with accurate measurements of hardness ratio and flux density.

We begin with a conic search in the Chandra database with a radius of 2 arcminutes around the center of each host galaxy to see whether any X-ray sources lie in that area. Out of the 300 host galaxies, 39 of them have some x-ray point sources. For the rest, they either do not contain any X-ray point sources or are not in the range of Chandra observation. The choice of 2 arcminutes as the initial filter helps to exclude galaxies that are not in Chandra observations and to ensure the X-ray point sources coincident with the span of the galaxies. As seen in the figure 1, some x-ray point sources lie far away from the center of the host galaxy, and some may even be beyond the span of the visible disk. Applying the same approach with a radius of 10 arcseconds further restricts the X-ray sources very close to the center of the galaxies, yielding 25 positive matches.

Other useful data archives that play a role in the later analysis are the Wide-field Infrared Survey Explorer (WISE) (Wright et al. 2010) and Galaxy Evolution Explorer (GALEX) (Bianchi et al. 2017). The first archive contains data measuring the sky in mid-infrared, and in particular, it gives flux density at $22\mu m$. The latter detects galaxies at near-UV and far-UV spectrum. Doing the same search with the radius of 10 arcseconds around the center of the 25 galaxies leaves 18 final candidates. They are our primary target of analysis in the later section. See figure 1 for the final list.

3. DATA ANALYSIS

With the three catalogs decided, we need relevant data from each of them. In the Chandra archive, the column titled `flux_aper_h` gives information on the background-subtracted, aperture-corrected hard-band energy fluxes. It represents an energy band of 2-10 keV. For each of the 18 galaxies, there are in general more than one x-ray point source within 10 arcseconds around the center. To fully account for all of them, we take the average of all point sources with valid data in Chandra. According to the formula

$$L = 4\pi d^2 f,$$

where L is the intrinsic luminosity of the source in $erg \cdot s^{-1}$, d is the distance of the source in cm and f is apparent brightness (flux) of the source in $erg \cdot s^{-1} \cdot cm^{-2}$, the calculated luminosities of an individual galaxy in hard X-ray sources are in the range $10^{38} - 10^{41}\ erg \cdot s^{-1}$. They agree with Eddington's luminosities and indicate the presence of black holes at the center. The high luminosity of X-ray may be due to active galactic nucleus (AGN), XRBs, or BHs. And indeed, some of the galaxies are classified as AGNs (NGC 4589) or Seyfert (NGC2783).

To further investigate their properties, we need flux of far-UV from GALEX and flux of 22μm from WISE. The calibrated ab magnitude of far-UV is available in the python library `astroquery.mast` under the column named `fuv_mag`, whereas the vega magnitude of $22\mu m$ is available in WISE archive under the column named `w4mpro`. For galaxies with multiple point sources, their recorded magnitude in our table are the simple average of all valid data. Using the calibration from the official documents [1 2], we calculate their respective flux in $erg \cdot s^{-1} \cdot cm^{-2}$. Following Kennicutt & Evans (2012) and Hao et al. (2011), the formula

$$\log(SFR) = \log(L(FUV)_{corr}) - 43.35$$

gives a good estimate of the dust-corrected star formation rates (SFR), where

$$L(FUV)_{corr} = L(FUV)_{obs} + 3.89 \times L(25\mu m)_{obs}.$$

Here, $L(FUV)_{obs}$ is the observed luminosity of far-UV in $erg \cdot s^{-1}$ and $L(25\mu m)_{obs}$ is the observed luminosity of $25\mu m$ in $erg \cdot s^{-1}$. Their $25\mu m$ luminosities come from Infrared Astronomical Satellite (IRSA), but this catalog covers very few of our interesting galaxies. Since WISE is much more sensitive than IRSA and its coverage is more satisfactory, we replace the $25\mu m$ luminosity from ISRA with the $22\mu m$ luminosity from WISE and expect the ratio of the flux densities close to 1 (Jarrett et al. 2013). Table 2 gives the derived $L(25\mu m)_{obs}$, $L(FUV)_{obs}$, and SFR for the 18 galaxies.

Finally, we estimate the expected luminosity from XRBs given their masses and SFRs using the relation by Lehmer et al. (2010),

$$L(XRB)_{2-10keV} = \alpha M_\star + \beta SFR,$$

where $\alpha = (9.05 \pm 0.37) \times 10^{28}\ erg \cdot s^{-1} \cdot M_\odot^{-1}$ and $\beta = (1.62 \pm 0.22) \times 10^{39}\ erg \cdot s^{-1} \cdot (M_\odot \cdot yr^{-1})^{-1}$. Figure 2 shows a plot of the observed hard X-ray luminosity versus the expected luminosity from XRBs. The black line represents a one-to-one relation. In the figure, 15 out of 18 galaxies have more observed luminosity than expected luminosity from XRB. It is likely due to other strong X-ray point sources in these galaxies. Further

[1] https://asd.gsfc.nasa.gov/archive/galex/FAQ/counts_background.html

[2] https://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec4_4h.html#example

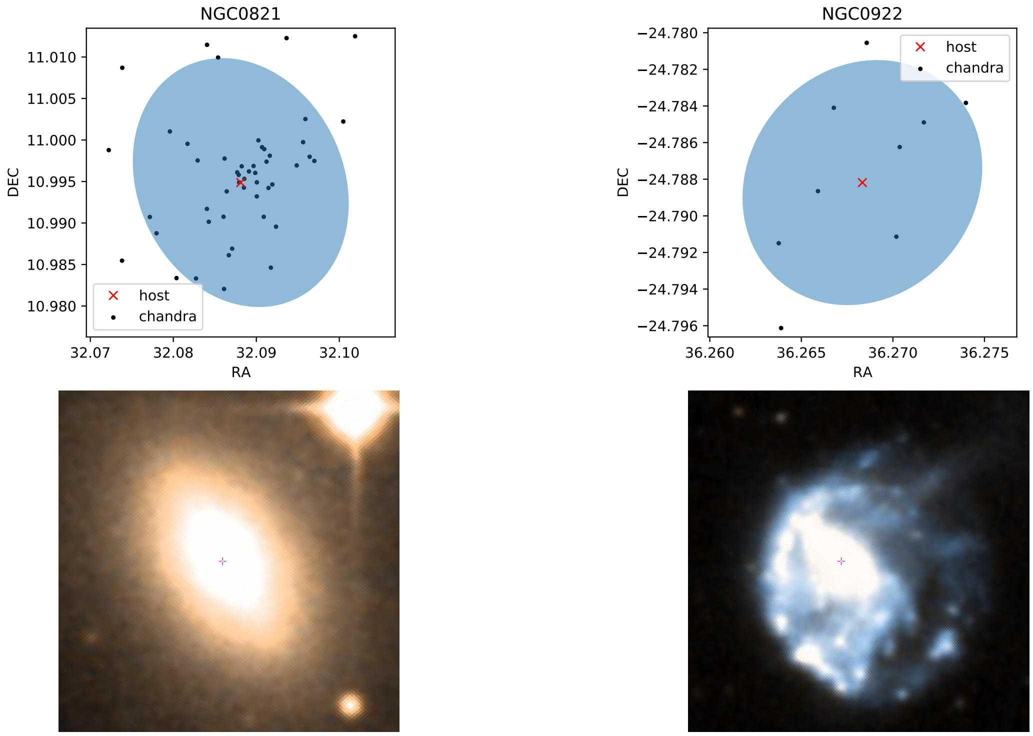

Figure 1. Two candidates from the SAGA catalog: on the left is NGC0821 and on the right is NGC0922. The first row gives a plot of the two galaxies, with the blue ellipse representing the visible disk of the galaxy, black dots representing each X-ray point source from Chandra, and the red cross representing the center of the galaxy. The second row gives the real images from DSS for comparison. As seen in the plots that there are many X-ray point sources very near the galactic center of NGC0821, but almost no X-ray point sources near to the galactic center of NGC0922.

investigation on these galaxies can explain the situation more conclusively. The remaining 3 galaxies have lower observed luminosity compared to that from XRBs, and this indicates that the galactic center consists mostly of XRBs.

4. DISCUSSION AND CONCLUSION

We analyze the X-ray characteristics for 18 Milky Way analogs and compute both the observed X-ray luminosity and expected X-ray luminosity. The high correlation indicates these galaxies contain XRBs at their galactic centers. In collecting data from different datasets, we record the average value. It can potentially affect the final result since the most intense source may not come from the most center in the galaxy. Moreover, due to the uncertainty in determining the galactic center, we may include unwanted data. Another caveat we do not focus on is that the selected sources are in the plane of the galactic disk. It is likely that those point sources do not lie inside the galaxy in 3 dimensions but only appear to be inside in a 2-dimensional perspective. Extra efforts are needed to filter out this error. Finally, our 18 candidates constitute a small sample size compared to the over 300 Milky Way analogs. The major hindrance

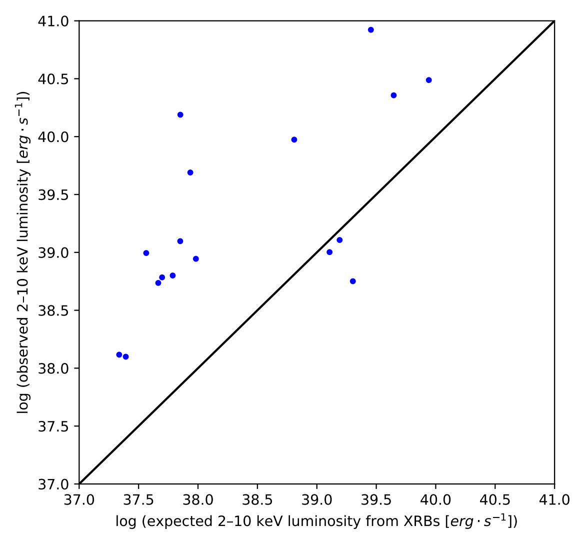

Figure 2. Expected luminosity vs observed luminosity. The blue dots represent the 18 galaxies and the black line represents a one-to-one correspondence.

is that not many of the candidates have all valid data in

ID	COMMON_NAME	RA	DEC	DIST	M_HALO
0	NGC0821	32.088030	10.994985	23.345329	12.321141
1	NGC2778	138.101577	35.027497	32.213418	11.856141
2	NGC2782	138.521169	40.113726	39.902490	12.445141
3	NGC3414	162.817584	27.975039	24.092068	12.337141
4	NGC3610	169.605291	58.786236	32.508730	12.283141
5	NGC4030	180.098356	-1.100072	23.120868	12.337141
6	NGC4589	189.354291	74.191861	25.917911	12.309141
7	NGC4750	192.530042	72.874472	27.656677	12.306141
8	NGC4939	196.059813	-10.339569	37.653036	12.464141
9	NGC5170	202.453191	-17.966498	27.618494	12.354141
10	NGC5198	202.547541	46.670806	37.583476	12.664141
11	NGC5347	208.324161	33.490824	34.556760	11.950141
12	NGC5422	210.175128	55.164451	30.051567	12.151141
13	NGC5678	218.023359	57.921432	28.080187	12.264141
14	NGC5728	220.599537	-17.253005	30.157824	12.205141
15	NGC6278	255.209689	23.011038	39.315385	12.303141
16	NGC6925	308.585718	-31.980883	33.358000	12.602141
17	NGC7507	348.031554	-28.539653	24.740017	12.691141

Table 1. Our final list of 18 galaxies from the SAGA catalog with valid data in Chandra, GALEX, and WISE. Column 1 gives an index for each galaxy for later reference. Column 2 gives the common names for the galaxies. Columns 3 and 4 give the right ascension and declination for each galaxy in degrees. Column 5 gives the distance of each galaxy to the Sun in Mpc. Column 6 gives the halo masses relative to the solar mass in the log10 scale. All data are taken from SAGA.

all three datasets. There are likely other data archives with relevant or even better information, but we do not go deep in this direction. For further investigation, one can try to consult more data archives to sample more galaxies.

REFERENCES

Lulu Liu et al 2011 ApJ 733 62

Kormendy, J., & Ho, L. C. 2013, ARA&A, 51, 511

Ghez, A. M., Salim, S., Weinberg, N. N., et al. 2008, ApJ, 689, 1044. doi:10.1086/592738

Mao, Y.-Y., Geha, M., Wechsler, R. H., et al. 2021, ApJ, 907, 85. doi:10.3847/1538-4357/abce58

Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868. doi:10.1088/0004-6256/140/6/1868

Evans, I. N., Primini, F. A., Glotfelty, K. J., et al. 2010, ApJS, 189, 37. doi:10.1088/0067-0049/189/1/37

Bianchi, L., Shiao, B., & Thilker, D. 2017, ApJS, 230, 24. doi:10.3847/1538-4365/aa7053

Kennicutt, R. C. & Evans, N. J. 2012, ARA&A, 50, 531. doi:10.1146/annurev-astro-081811-125610

Hao, C.-N., Kennicutt, R. C., Johnson, B. D., et al. 2011, ApJ, 741, 124. doi:10.1088/0004-637X/741/2/124

Lehmer, B. D., Alexander, D. M., Bauer, F. E., et al. 2010, ApJ, 724, 559. doi:10.1088/0004-637X/724/1/559

Lemons, S. M., Reines, A. E., Plotkin, R. M., et al. 2015, ApJ, 805, 12. doi:10.1088/0004-637X/805/1/12

Jarrett, T. H., Masci, F., Tsai, C. W., et al. 2013, AJ, 145, 6. doi:10.1088/0004-6256/145/1/6

ID	FLUX_APER_H	W4_MAG	FUV_MAG	FUV_LUM	W4_LUM	LOG_SFR	EST_X_LUM	X_LUM
0	1.926430e-15	7.594	19.5339	40.879012	40.833772	-1.817277	37.392238	38.099064
1	1.053158e-15	8.600	19.9299	41.000271	40.711045	-1.872812	37.336703	38.116478
2	1.615647e-13	2.224	15.1997	43.078296	43.447372	0.732603	39.942118	40.488258
3	7.053582e-14	6.378	18.0219	41.511164	41.347520	-1.274320	37.935195	39.690069
4	6.960982e-15	6.814	18.8655	41.433966	41.433372	-1.227198	37.982317	38.944581
5	8.810962e-15	3.215	13.9192	43.116472	42.576980	0.093463	39.302978	38.750943
6	7.571884e-15	7.131	18.7718	41.274651	41.109772	-1.511731	37.697784	38.784315
7	1.028903e-13	5.370	15.1494	42.779988	41.870572	-0.399980	38.809536	39.973885
8	1.078566e-12	3.878	14.478	43.316578	42.735372	0.272002	39.481517	41.262358
9	5.967655e-15	7.176	19.662	40.973776	41.146972	-1.543956	37.665559	38.736115
10	3.735433e-15	7.861	19.0422	41.489289	41.140566	-1.422531	37.786985	38.800246
11	1.591308e-13	2.544	18.6248	41.583322	43.194438	0.437112	39.646627	40.356731
12	9.136335e-15	7.657	19.8735	40.962512	41.027906	-1.645381	37.564134	38.994417
13	1.356275e-14	3.516	15.371	42.704576	42.625372	-0.017905	39.191610	39.107059
14	7.686343e-13	2.736	17.9933	41.717642	42.999372	0.245118	39.454633	40.922431
15	8.354760e-14	7.465	20.0434	41.127906	41.338097	-1.358081	37.851434	40.188970
16	7.550411e-15	5.470	14.6536	43.141126	41.993372	-0.102745	39.106770	39.002282
17	1.706946e-14	6.860	17.8702	41.594866	41.177772	-1.359133	37.850382	39.096931

Table 2. The calculation of respective data of the 19 galaxies. Column 1 gives the ID reference to table 1. Column 2 gives the x-ray flux in $erg \cdot s^{-1} \cdot cm^{-2}$ obtained from Chandra. Column 3 gives the $22\mu m$ vega magnitude from WISE. Column 4 gives the far-UV ab magnitude from GALEX. Columns 5 and 6 give the calculated luminosity of far-uv and $22\mu m$ in $erg \cdot s^{-1}$ in log10 scale. Column 7 gives the calculated SRF in $M_{\odot} \cdot yr^{-1}$ in log10 scale. Column 8 gives the estimated X-ray luminosity from XRB in $erg \cdot s^{-1}$ in log10 scale. Column 9 gives the observed X-ray luminosity in $erg \cdot s^{-1}$ in log10 scale.