Communications of BAO, Vol. 71, Issue 2, 2024, pp. 345-350

Deciphering Galactic Halos: A Detailed Review of Star Formation in NGC 5128 (Cen A)

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Abstract

NGC 5128 (Centaurus A), the closest giant elliptical galaxy outside the Local Group to the Milky Way, is one of the brightest extragalactic radio sources. It is distinguished by a prominent dust lane and powerful jets, driven by a supermassive black hole at its core. Using previously identified long-period variable (LPV) stars from the literature, this study aims to reconstruct the star formation history (SFH) of two distinct regions in the halo of NGC 5128. These regions reveal remarkably similar SFHs, despite being located about 28 kpc apart on opposite sides of the galaxy's center. In Field 1, star formation rates (SFRs) show notable increases at approximately 800 Myr and 3.8 Gyr ago. Field 2 exhibits similar peaks at these times, along with an additional rise around 6.3 Gyr ago. The increase in SFR around 800 Myr ago is consistent with earlier research suggesting a merger event. Since no LPV catalog exists for the central region of NGC 5128, we focused our investigation on its outer regions, which has provided new insights into the complex evolutionary history of this cornerstone galaxy. The SFH traced by LPVs supports a scenario in which multiple events of nuclear activity have triggered episodic, jet-induced star formation.

Keywords: *stars: AGB and LPV – stars: formation – galaxies: halos – galaxies: evolution – galaxies: star formation – galaxies: individual: NGC 5128*

1. Introduction

Our position within the Local Group (LG) provides an excellent opportunity to study the resolved stellar populations of spiral galaxies, enhancing our understanding of their formation and evolution. However, because the LG lacks a giant elliptical (GE) galaxy, our knowledge of such systems relies on observations of the nearest elliptical galaxies in neighboring groups. NGC 5128 (Centaurus A), situated 3.8 Mpc away ($\mu = 27.87 \pm 0.16$ mag; Rejkuba et al., 2004, and $E(B-V) = 0.15 \pm 0.05$ mag; Rejkuba, M., 2004a), presents a rare opportunity to study a nearby GE galaxy in details (Harris et al., 1999; Charmandaris et al., 2000; Rejkuba, M., 2004a, 2005), as it resides within the Centaurus galaxy group (Karachentsev, 2005).

NGC 5128 is considered a post-merger galaxy (Peng et al., 2002) and is one of the few halos that has been resolved into individual stars (Rejkuba et al., 2011). The stellar populations in NGC 5128's halo serve as crucial indicators of its star formation history, revealing evidence of past interactions and mergers.

The active galactic nucleus (AGN) at the center of NGC 5128 drives powerful radio jets, providing the closest example of this galactic outflows (Crockett et al., 2012). How AGN activity influences star formation and the evolution of its host galaxy remains a crucial but unresolved question in galaxy formation and evolution theory (Ciotti & Ostriker, 1997; Silk & Rees, 1998, 2005; Binney, 2004; Springel et al., 2005; Sijacki et al., 2007; Schawinski et al., 2007).

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doi: https://doi.org/10.52526/25792776-24.71.2-345

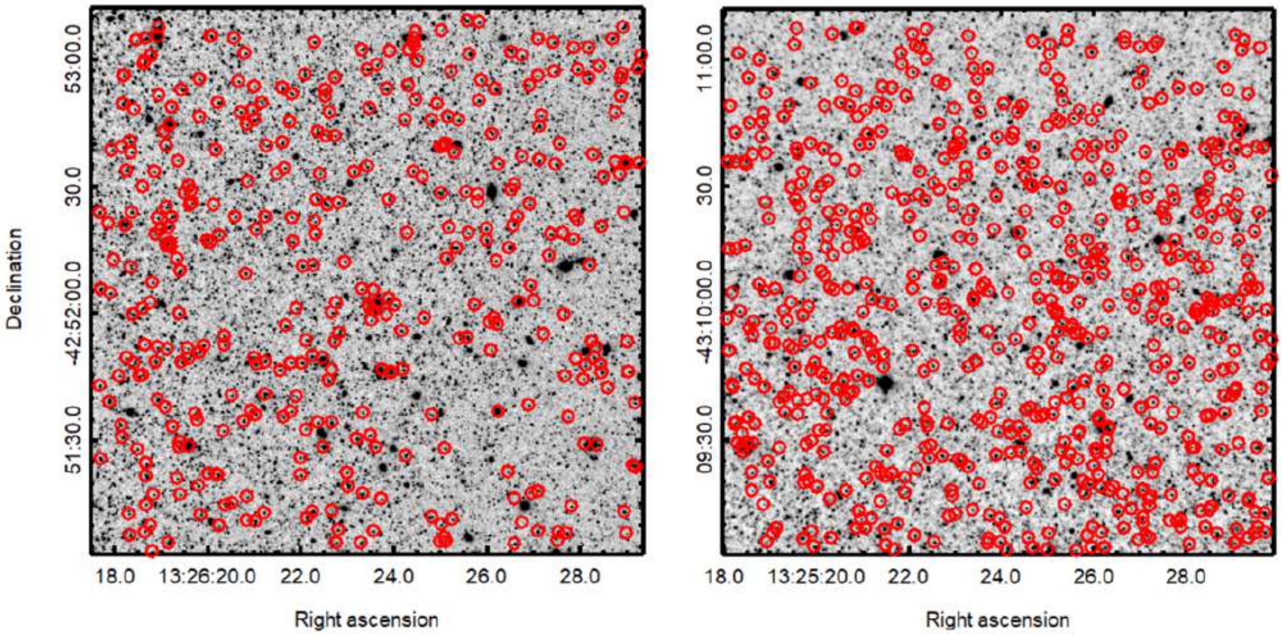

Figure 1. The images of the fields studied here (each approximately 2.3×2.3 arcminutes) are shown. Red circles indicate the locations of the selected LPV stars. (Left panel) The northwestern field is centered at $\alpha = 13^h\ 26^m\ 23^s\!.5$, $\delta = -42^\circ\ 52'\ 0''$, on the eminent northeastern part of the halo, at a distance of $\sim 17'$ (~ 18.8 kpc) from the center of the galaxy presented by Ma et al., 1998, with dimensions of $2'\!.28 \times 2'\!.30$ (5.7 kpc^2). (Right panel) The southern field is centered at $\alpha = 13^h\ 25^m\ 26^s$, $\delta = -43^\circ\ 10'\ 0''$, at a distance of $\sim 9'$ (~ 9.9 kpc) from the center, with dimensions of $2'\!.25 \times 2'\!.31$ (5.7 kpc^2).

The star formation history is essential for understanding galaxy formation and evolution. In resolved galaxies, SFH is usually derived from color–magnitude diagrams (CMDs) of individual stars, revealing signatures of various stellar populations (e.g., Tolstoy & Saha, 1996; Holtzman et al., 1999; Olsen, 1999; Dolphin, 2002,Javadi et al., 2011b). However, this analysis is typically limited to a few dozen galaxies, mostly within our Local Group, due to observational constraint.

This work aims to determine the SFH of two small fields in the halo of NGC 5128 by using long-period variable stars as tracers, to explore the connection between the halo's SFH and its merger history.

2. Data

We utilized near-infrared data published by Rejkuba, M., 2004b and analyzed by Rejkuba et al., 2003. This catalog was obtained using the ISAAC instrument on the ESO Paranal UT1 Antu 8.2 m Very Large Telescope, covering two distinct fields in the northwestern and southern regions of the halo of NGC 5128 (referred to as Field 1 and Field 2, respectively), as shown in Figure 1.

Rejkuba, M. (2004a) identified 15,574 and 18,098 stars in Fields 1 and 2, respectively. However, our focus is on long-period variable stars with periods exceeding 70 days, which form the basis for a method for constructing the star formation history as developed by Javadi et al. (2011a).

Rejkuba et al. (2003) identified LPV stars using multi-epoch photometry in the Ks band, along with single-epoch photometry in the Js and H bands, in two mentioned fields. However, based on the specified criteria, we selected 395 LPV stars in Field 1 and 671 in Field 2. The distribution of these selected LPV stars, marked by red circles, is displayed in Figure 1.

3. Method

As mentioned in the previous section, Javadi et al. (2011a) developed a method to calculate star formation histories based on long-period variable stars. During the LPV phase, stars reach their peak luminosity, providing a valuable opportunity to establish a strong correlation between birth mass and this peak. Based

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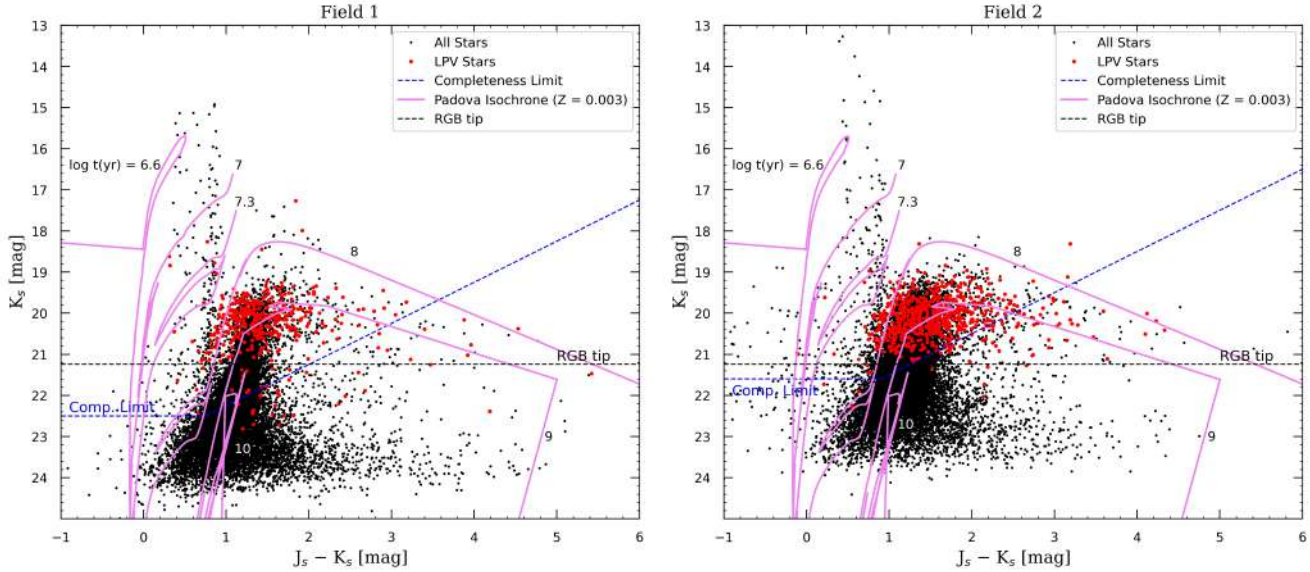

Figure 2. The K_s vs. $J_s - K_s$ color-magnitude diagram (CMD) shows stars with at least three K_s-band detections (black dots) and long-period variable (LPV) stars (red dots) in Field 1 (left) and Field 2 (right). The black and blue dotted lines represent the tip of the red giant branch (RGB) and the completeness limit magnitudes, respectively, for each field (Rejkuba et al., 2003). The purple lines indicate theoretical stellar isochrones for a metallicity of $Z = 0.003$ across six different ages (Marigo et al., 2017).

Table 1. The age-metallicity relation investigated by Woodley et al. (2009) and Yi et al. (2004) assuming $Z_\odot = 0.0198$ (Rejkuba et al., 2011).

Woodley et al., 2009		Yi et al., 2004	
Age range (Gyr)	Z	Age range (Gyr)	Z
age $\geq$ 12	0.001	age $\geq$ 10	0.0003
8 $\leq$ age <12	0.003	6 $\leq$ age <10	0.001
6.5 $\leq$ age <8	0.006	4 $\leq$ age <6	0.003
5.5 $\leq$ age <6.5	0.008	3 $\leq$ age <4	0.010
3 $\leq$ age <5.5	0.010	2 $\leq$ age <3	0.020
2 $\leq$ age <3	0.020	age <2	0.039
age <2	0.030		

on this correlation, relations—including the birth mass-luminosity, age-mass, and pulsation duration relations—can be derived for each metallicity from the Padova stellar evolutionary models (Marigo et al., 2017). By inputting the stars' magnitudes into these relations, we can determine the components of an equation that statistically reconstructs the star formation history of galaxies based on the initial mass function.

$$\xi(t) = \frac{dn'(t)}{\delta t} \; \frac{\int_{\min}^{\max} f_{\rm IMF}(m) m \; dm}{\int_{m(t)}^{m(t+dt)} f_{\rm IMF}(m) \; dm}, \tag{1}$$

where m is birth mass and $f_{\rm IMF}(m)$ is Kroupa initial mass function (IMF) (Kroupa, 2001).

As shown in Figure 2, we expect all LPV stars to be located near the peaks of the isochrones derived from the Padova stellar evolutionary models. However, some stars appear spread into redder regions due to surrounding dust. To correct for dust effects, these stars need to be shifted back to the isochrone peaks before their magnitudes are used in the mentioned statistical equations.

This method, which has since been applied in a variety of studies (Javadi et al., 2011a, 2011b, 2017; Rezaei kh. et al., 2014; Hamedani Golshan et al., 2017; Hashemi et al., 2018; Navabi et al., 2021; Saremi et al., 2020; Parto et al., 2023; Abdollahi et al., 2023;Aghdam et al., 2024; Khatamsaz et al., 2024), considers a range of metallicities to define the epochs of star formation for each case and enables comparisons among them.

However, we go a step further by incorporating the age-metallicity relation, which provides an opportunity to address uncertainties in the metallicity. To elaborate, this approach allows us to determine the

doi: https://doi.org/10.52526/25792776-24.71.2-345

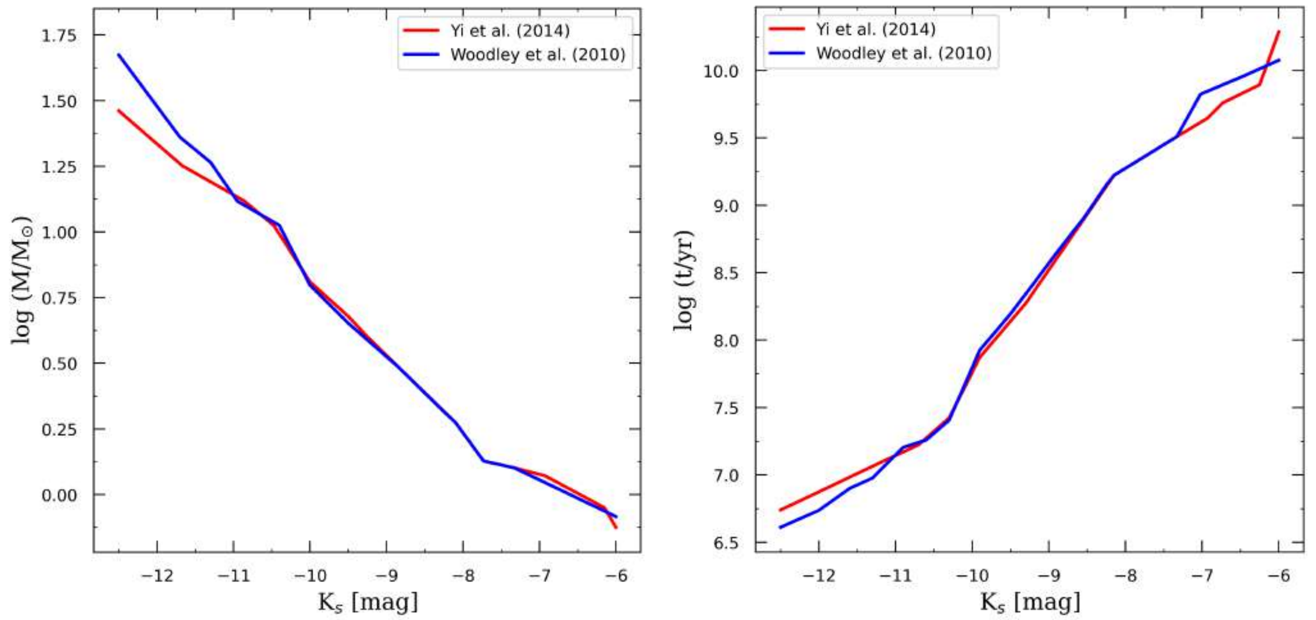

Figure 3. The mass–luminosity (left panel) and age–luminosity (right panel) relations, considering the AMRs determine by Yi et al. (2004) (red line) and Woodley et al. (2009) (blue line).

metallicity of the galaxy across each age range, as presented in Table 1.

We redefined the mass-luminosity and age-mass relations based on the age-metallicity relation (AMR), resulting in a single, unified relation that encompasses the full range of metallicities experienced by the galaxy. Figure 3 illustrates these relations for the models determined by Yi et al. (2004) and Woodley et al. (2009). As shown, the trends in these diagrams are similar, with only slight differences at the beginning and end of the intervals. Using the AMR approach, we can now overcome the metallicity degeneracy and establish Equation 1 to derive the SFH for the two separate fields.

4. Results and Discussion

In our analysis of the SFH of NGC 5128, illustrated in Figure 4, Field 1 exhibited two major star formation epochs: one approximately 3.6 billion years ago and another around 800 million years ago. Field 2, however, showed three significant epochs, occurring roughly 6.3 billion, 3.6 billion, and 800 million years ago. The latter two epochs align with those in Field 1, suggesting a connection between these distant regions, despite being separated by 28 kpc on opposite sides of the galaxy. This similarity in SFH across such large distances implies shared galactic-scale influences.

Comparing our results with previous studies reveals further insights into the history of NGC 5128. Evidences such as the galaxy's unusual structure (Graham, 1979), optical and neutral hydrogen shells (Malin et al., 1983; Peng et al., 2002; Schiminovich et al., 1994), and ongoing star formation suggest a history of mergers and interactions (Rejkuba, M., 2004b). Specifically, literature indicates a major merger with a smaller, gas-rich galaxy around 1 Gyr ago (Malin et al., 1983; Sparke, 1996), which aligns with our observed peak in star formation around the previous 800 Myr. Additionally, a possible minor merger could explain the secondary star formation peak, indicating this galaxy has undergone multiple interactions over time.

Furthermore, NGC 5128's central supermassive black hole has likely driven active galactic nucleus (AGN) activity, fueled by abundant cold gas. Such activity, as noted in studies by Saxton et al., 2001 and Hardcastle et al., 2009, has been linked to increased the star formation rate. The age estimates for the nuclear molecular layer (∼150 Myr) and inner lobes (∼30 Myr) suggest that the AGN was active well before these epochs, potentially contributing to the sustained rise in star formation observed up to around 800 Myr ago.

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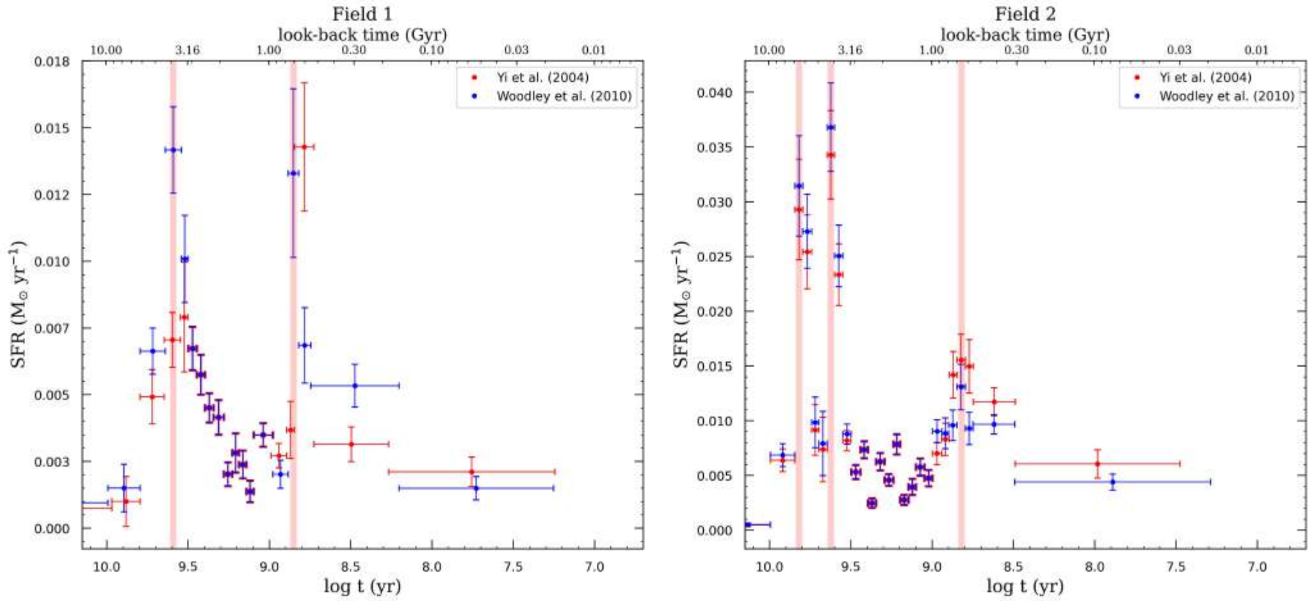

Figure 4. The SFH derived using the age-metallicity relations (AMRs) from Yi et al. (2004) (red markers) and Woodley et al. (2009) (blue markers) is shown for Field 1 (left panel) and Field 2 (right panel). Highlighted regions indicate the peaks of star formation during major epochs.

5. Conclusion

In this study, we investigated the star formation history (SFH) of NGC 5128, the nearest giant elliptical galaxy to the Local Group, by employing a statistical approach based on long-period variable (LPV) stars. Our analysis focused on two distinct regions within the halo of this galaxy, providing insights into the star formation activity in the outer regions of this unique system. Key findings include:

- A novel method based on the age-metallicity relation of LPV stars was introduced and employed to investigate the SFH of NGC 5128.
- Despite their significant separation, both studied regions exhibited a similar SFH, suggesting equivalent evolutionary influences across the galaxy.
- Evidence of peaks in star formation supports the occurrence of a past collision or merger in NGC 5128.
- Our findings indicate that active galactic nucleus (AGN) activity can enhance the star formation rate in galaxies.

References

Abdollahi H., et al., 2023, Astrophys. J. , 948, 63

Aghdam S. T., et al., 2024, Astrophys. J. , 972, 47

Binney J., 2004, MNRAS, 347, 1093

Charmandaris V., Combes F., van der Hulst J. M., 2000, Astron. Astrophys. , 356, L1

Ciotti L., Ostriker J. P., 1997, Astrophys. J. Lett. , 487, L105

Crockett R. M., et al., 2012, MNRAS, 421, 1603

Dolphin A. E., 2002, MNRAS, 332, 91

Graham J. A., 1979, Astrophys. J. , 232, 60

Hamedani Golshan R., Javadi A., van Loon J. T., Khosroshahi H., Saremi E., 2017, Mon. Not. R. Astron. Soc. , 466, 1764

Hardcastle M. J., Evans D. A., Croston J. H., 2009, Mon. Not. R. Astron. Soc. , 396, 1929

Harris G. L. H., Harris W. E., Poole G. B., 1999, Astron. J. , 117, 855

Hashemi S. A., Javadi A., van Loon J. T., 2018, MNRAS, 483, 4751

doi: https://doi.org/10.52526/25792776-24.71.2-345

Holtzman J. A., et al., 1999, The Astronomical Journal, 118, 2262

Javadi A., van Loon J. T., Mirtorabi M. T., 2011a, MNRAS, 411, 263

Javadi A., van Loon J. T., Mirtorabi M. T., 2011b, MNRAS, 414, 3394

Javadi A., van Loon J. T., Khosroshahi H. G., Tabatabaei F., Hamedani Golshan R., Rashidi M., 2017, Mon. Not. R. Astron. Soc. , 464, 2103

Karachentsev I. D., 2005, Astron. J. , 129, 178

Khatamsaz F., Abdollahi M., Abdollahi H., Javadi A., Van Loon J., 2024, in IAU General Assembly. p. 648

Kroupa P., 2001, Mon. Not. R. Astron. Soc. , 322, 231

Lamers, H. J. G. L. M. Kruijssen, J. M. D. Bastian, N. Rejkuba, M. Hilker, M. Kissler-Patig, M. 2017, A&A, 606, A85

Ma C., et al., 1998, The Astronomical Journal, 116, 516

Malin D., Quinn P., Graham J., 1983, Astrophys. J. , 272, L5

Marigo P., et al., 2017, Astrophys. J. , 835, 77

Morganti R., Killeen N. E. B., Ekers R. D., Oosterloo T. A., 1999, MNRAS, 307, 750

Navabi M., et al., 2021, Astrophys. J. , 910, 127

Olsen K. A., 1999, The Astronomical Journal, 117, 2244

Parto T., et al., 2023, Astrophys. J. , 942, 33

Peng E. W., Ford H. C., Freeman K. C., White R. L., 2002, Astron. J. , 124, 3144

Rejkuba, M. 2004a, A&A, 413, 903

Rejkuba, M. 2004b, A&A, 413, 903

Rejkuba M., Minniti D., Silva D. R., 2003, Astron. Astrophys. , 406, 75

Rejkuba M., Greggio L., Zoccali M., 2004, Astron. Astrophys. , 415, 915

Rejkuba M., Greggio L., Harris W. E., Harris G. L. H., Peng E. W., 2005, Astrophys. J. , 631, 262

Rejkuba M., Harris W. E., Greggio L., Harris G. L. H., 2011, Astron. Astrophys. , 526, A123

Rezaei kh. S., Javadi A., Khosroshahi H., van Loon J. T., 2014, MNRAS, 445, 2214

Saremi E., et al., 2020, Astrophys. J. , 894, 135

Saxton C. J., Sutherland R. S., Bicknell G. V., 2001, Astrophys. J. , 563, 103

Schawinski K., Thomas D., Sarzi M., Maraston C., Kaviraj S., Joo S.-J., Yi S. K., Silk J., 2007, MNRAS, 382, 1415

Schiminovich D., van Gorkom J. H., van der Hulst J. M., Kasow S., 1994, Astrophys. J. Lett. , 423, L101

Sijacki D., Springel V., Di Matteo T., Hernquist L., 2007, MNRAS, 380, 877

Silk J., 2005, MNRAS, 364, 1337

Silk J., Rees M. J., 1998, Astron. Astrophys. , 331, L1

Sparke L. S., 1996, Astrophys. J. , 473, 810

Springel V., Di Matteo T., Hernquist L., 2005, The Astrophysical Journal, 620, L79

Tolstoy E., Saha A., 1996, Astrophys. J. , 462, 672

Woodley K. A., Harris W. E., Puzia T. H., Gómez M., Harris G. L., Geisler D., 2009, The Astrophysical Journal, 708, 1335

Yi S., Peng E., Ford H., Kaviraj S., Yoon S.-J., 2004, MNRAS, 349, 1493

doi: https://doi.org/10.52526/25792776-24.71.2-345