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Baryonic Tully-Fisher relation and star formation rate

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Abstract

We investigated the relation between rotational velocity, baryonic mass, and star formation rate (SFR) for several sample galaxies, and found a fundamental plane in three dimension on which those galaxies are located. In order to understand the galaxy evolution, we first need to investigate physical properties of galaxies. Many discussions have already been made and shown as a form of scaling laws that connect two physical properties of galaxies, such as the Tully-Fisher relation, the baryonic Tully-Fisher relation, star-formation main sequence, the Schmidt-Kennicutt law, and so on. In reality, however, they exist seperately. Therefore, when it comes to understanding and determining the galaxy evolution, it is essential to combine those scaling laws to construct a unified theory that explains the galaxy evolution universally in terms of their physical properties. In this study, we compiled observational data for 130 galaxies to confirm the baryonic Tully-Fisher relation (BTFR), star-formation main sequence, and lastly found a fundamental plane in three dimension. This would be the first step to see what properties we need to concern primarily to establish the unified theory.

1 Introduction

To understand the galaxy evolution, it is one of the most important viewpoints to know the relation between dark halos and galaxies because galaxies form and evolve in these dark halos potential. In the history of the Universe, dark halos first formed and merged with each other as time passed, and first stars were born inside these dark halos. Then, galaxies have formed there and evolved.

The Tully-Fisher relation (Tully & Fisher. 1977: TFR) is an empirical relation between the galaxy rotational velocity and luminosity. This relation works effectively to determine the distance of relatively nearby galaxies. However, the TFR actually does not just provide the way to determine the distances, but also work as an important relation to connect the baryon and dark matter of a galaxy. The dynamical mass, which is the sum of baryonic mass and dark matter mass of a galaxy, generates the rotational velocity, and the stars contained in a galaxy contribute to its luminosity. Thus, the tightness in the TFR implies there would be a strong relation between dark matter and baryon. Although the TFR is a well-established linear relation, it had been known that low mass galaxies are deviated from this tight power-law relation.

McGaugh (2000) discoverd that this power-law realtion is restored if we use baryonic mass instead of luminosity. (Baryonic mass is the sum of stellar mass and gas mass of a galaxy.) This revised power-law relation is called the baryonic Tully-Fisher relation (BTFR.) This power-law indicates baryonic mass is more fundamental properties than luminosity because low mass galaxies basically contatin a lot of gas that is still not turned into stars and do not creat stars as effectively as bright galaxies do. Since the rotational velocity is generated in the potential of dynamical mass, the BTFR is a strong standpoint to invest the galaxy evolution as an interaction of dark matter and baryon in general. It is now often discussed to how extent we can extend the BTFR towards much lower mass galaxies.

Another intersting empirical relation of galaxies is star-formation main sequence (SFMS.) Star-forming galaxies gather and get aligned to make this prominent sequence on the two dimensional plane spanned by stellar mass and specific star formation rate (SSFR.) SSFR is defined by

$$\mathrm{SSFR} = \frac{\mathrm{SFR}}{M_*} \tag{1}$$

Here, SFR is a rate at which a galaxy creats stars in the unit of $M_\odot$ year^{-1}, and M_* is stellar mass that a galaxy hold now.

If only dark matter were involved in the galaxy evolution, the related Physics would be relatively simple because dark matter basically interacts with each other only gravitationally. But, the active evolution includes baryons and baryons involve many physical processes to make this evolution complicated. Thus, the analysis of galaxy evolution cannot stand without research of the baryonic properties. The SFMS is an star-forming aspect of these baryonic properties and represents the combination of star formation histroy of a galaxy and its current stellar mass. Then, we expected a similar relation would exist between SFR and baryonic mass as well.

Although these two relations seem to be obvious, the physical justification for the reason why they are so tight is actually still under debate.

In this work, we considered these two empirical relations to find fundamental properties underlying all galaxies on an analytic basis of observational data. In Section 2, we show the data we quoted from several papers. In Section 3, we plot the sample galaxies on several two dimensional planes and confirm the BTFR and SFMS. Moreover, we make three dimensional real space spanned by rotational velocity, total baryonic mass, and SFR to plot galaxies. This corresponds to an incorporation of two scaling laws: the BTFR and SFMS. We calculate a fit two dimensional plane on which these galaxies are located and finally find a fundamental plane that hold a relation between these three galactic properties. In Section 4, we briefly discuss some points from the outcomes. We conclude in Section 5, and list future prospects in Section 6.

2 Data

Ishikawa.H.J. (2013) quoted three papers: Torres-Flores et al. (2011), Gurovich et al. (2010), and McGaugh & Wolf. (2010). He calculated SFR by using AKARI and GALEX data, but the dwarf spheroidal satellite galaxies in McGaugh's paper are difficult to determine their SFR in this way. Therefore, Ishikawa finally excluded this data from his analysis. We also started from only Torres-Flores et al. (2011) and Gurovich et al. (2010). To make this fundamental property analysis reliable, we sought for more data of disk galaxies and lastly chose three other papers: Puech et al. (2010), Brosch et al. (2011), McGaugh. (2012).

Three samples from our data are shown at the top on the next page as an example. In total, we compiled 130 galaxies data.

3 Investigation and Result

We extracted the data of rotational velocity, stellar mass, gas mass, baryonic mass, and star formation rate from each paper. We abbreviate stellar mass as M_*, gas mass as M_{gas}, baryonic mass as M_{bar}, and rotational velocity as V_{rot} hereafter. If the gass mass and baryonic mass are not available, we convert HI mass to gas mass by

$$\begin{aligned} M_{\mathrm{gas}} &= 1.4 M_{\mathrm{HI}} && (2) \\ M_{\mathrm{bar}} &= M_* + M_{\mathrm{gas}} && (3) \end{aligned}$$

We plotted these data on several different planes and in a space. First, on M_{bar}-V_{rot} plane, we confirmed the BTFR in our data. We found the BTFR

$$\log M_{\mathrm{bar}} = 2.76 \log V_{\mathrm{rot}} + 4.08 \tag{4}$$

having the slope of 2.76, which is realtively small compared with the ones from previous research (e.g.

表 1: An example of sample galaxies (cited from Puech et al. 2010)

IAU ID	$V_{\rm flat}$	$\Delta V_{\rm flat}$	$\log(M_{\rm stellar} M_{\odot}^{-1})$	SFR	ΔSFR	$\log(M_{\rm gas} M_{\odot}^{-1})$	$\Delta\log(M_{\rm gas} M_{\odot}^{-1})$
J033210.25-274819.5	150	26	10.29	5.7	4.1	9.82	0.33
J033210.76-274234.6	550	123	11.44	8.5	0.2	9.89	0.04
J033212.39-274353.6	180	22	10.61	17.2	0.3	10.21	0.11

McGaugh & Wolf. 2010, Gurovich et al. 2010, Torres-Flores et al. 2011, and so on.)

Second, on SFR-$M_{\rm bar}$ plane, we found

$$\log {\rm SFR} = 1.30 \log M_{\rm bar} - 13.1. \tag{5}$$

Third, on SSFR-M_* plane, we found

$$\log {\rm SSFR} = -0.50 \log M_* - 4.35. \tag{6}$$

This shows the galaxies in our data also form SFMS.

Fourth, on SSFR-$M_{\rm bar}$ plane, we found

$$\log {\rm SSFR} = -0.60 \log M_* - 3.31. \tag{7}$$

This shows a similar power-law relation corresponding to the SFMS on the previous plane.

Finally, in SFR-$M_{\rm bar}$-$V_{\rm rot}$ three dimensional space, we found the realtion between these three properties as follows:

$$\log {\rm SFR} = -3.78 \log V_{\rm rot} + 1.99 \log M_{\rm bar} - 11.2 \tag{8}$$

This relation constructs a two dimensional fundamental plane which subsumes all galaxies on its surface. Here, we weighted each sample with the inverse of their error bars along the SFR axis.

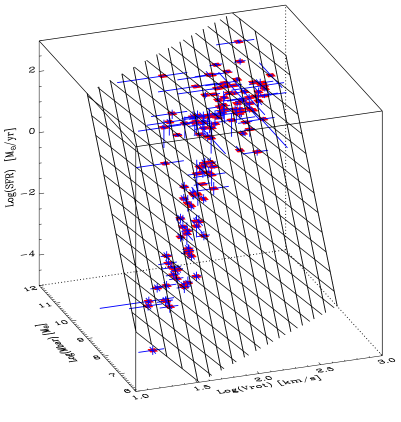

図 1: SFR-$M_{\rm bar}$-$V_{\rm rot}$ relation

4 Discussion

We actually have small deviations from the BTFR by Eq.(4) in the low mass region. This deviation can be a contribution not only from the low mass galaxies properties themselves, but also from the large mass galaxies properties in our samples. Those large mass galaxies are from Puech et al. (2010) and Brosch et al. (2011). Especially, Brosch et al. (2011) reported candidate high-mass disk galaxies that they provided in their paper deviate significantly from the TFR defined by lower mass galaxies, which leads to make a less inclined power-law relation.

We found a slgiht relation between baryonic mass and SFR by Eq.(5), but low mass galaxies and high mass galaxies seem to have different slopes.

We confirmed that the galaxies in our data also reproduce SFMS by Eq.(6) but several galaxies deviate far from the fitting line. These galaxies may have already passed their most active star-forming era and now finishing their star formations.

We presented that SSFR-$M_{\rm bar}$ relation by Eq.(7) also demonstrates SFMS.

We finally showed that the galaxies are on a fundamental plane defined by Eq.(8). This result has two big differences from the previous research done by Ishikawa.H.J. (2013). Ishikawa concluded that these three properties are connected as follows;

$$\log {\rm SFR} = 1.49 \log V_{\rm rot} + 0.552 \log M_{\rm bar} - 8.17. \tag{9}$$

First, SFR depends more on $V_{\rm rot}$ than on $M_{\rm bar}$ in Eq.(9), but depends more on $M_{\rm bar}$ than on $V_{\rm rot}$ in Eq.(8). Second, SFR is proportional to a power of $V_{\rm rot}$ in Eq.(9), but inversly proportional in Eq.(8).

We need to discuss these differences further and follow up what Eq.(8) physically mean.

5 Conclusion

We quoted data from Gurovich et al. (2010), Torres-Flores et al. (2011), Puech et al. (2010), Brosch et al. (2011), and McGaugh. (2012) to plot them on two dimensional graphs with different properties: $V_{\rm rot}$, M_*, $M_{\rm bar}$, SFR, and SSFR. Through these relations, we found the BTFR with a relatively small slope of 2.76. We confirmed SFMS and also a similar sequence on SSFR-$M_{\rm bar}$ plane.

Then, we demonstrated three dimensional relations between $V_{\rm rot}$, $M_{\rm bar}$, and SFR as

$$\log {\rm SFR} = -3.78 \log V_{\rm rot} + 1.99 \log M_{\rm bar} - 11.2.$$

This relation could underly all galaxies so that it represents the relation between dark matter, baryon, and the star formation history of galaxies.

6 Future Prospects

(1) We need to examine further the SFR dependence on $V_{\rm rot}$ and $M_{\rm bar}$ represented by Eq.(8) and find physical meaning in this relation.

(2) From 図 1 , mass range should be broad for the general analysis. This, however, also warn that more fundamental discussions require to treat different samples properly. For example, we can consider the age of galaxies or volume collection.

(3) In this work, the way to calculate SFR differes from each paper, therefore we should fix it. Using AKARI and GALEX data is one of the ways.

(4) We need to pay more careful attention to analytical procedures to deal with error bars, especially the errors along with $V_{\rm rot}$ and $M_{\rm bar}$ axes, which we did not take care of in this work.

(5) It is a current trend to investigate how far we can extend the BTFR toward lower mass galaxies, thus we should work on how far we can extend the fundamental plane in the three dimension as well. Observational progress for low mass but star-forming galaxies will be in demand. This is one of the expectations on SKA.

(6) There is another attracting scaling law related to star formation: Schmidt-Kennicutt law (KS-law). Since this is a realtion between two surface density quantities, radius will be the next appropriate property that we can take into account when we incoporate KS-law into the three dimensional relation Eq.(8). This immediately commands you to handle higher dimensional manifolds and involves high-dimensional analysis, such as PCA.

(7) To exmaine how the relation between dark matter and bayon evolved, we need to analyze the three dimensional relation at different redshift and establish the extended BTFR.

Reference

Tully,R.B., & Fihser,J.R. 1977, A&A, 54, 661

McGaugh,S.S., & Schombert,J.M., & Bothun,G.D., & Blok,W.J.G. 2000, APJ, 533, L99

McGaugh,S.S., & Wolf,J. 2010, APJ, 722, 248

Gurovich,S., & Freeman,K. & Jerjen,H., & Staveley-Smith,L., & Puerari,I. 2010, APJ, 140, 663

Torres-Flores,S. & Epinat,B., & Amram,P., & Plana,H., & Mendes de Oliveira,C. 2011, MNRAS, 416, 1936

Puech,M., & Hammer,F., & Flores,H., & Delgado-Serrano,R., & Rodrigues,M., & Yang,Y. 2010, A&A, 510, A68

Brosch,N., & Spector,P., & Zitrin,A. 2011, MNRAS, 415, 431

McGaugh,S. 2012, APJ, 143, 40

Ishikawa,H.J. 2013, Master Thesis, Nagoya University