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Estimation of galaxy SFRs from low radio frequencies

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Abstract

We present a global relation between the low-frequency and infrared (IR) emissions in star-forming galaxies compiled by the Herschel Reference Survey. The GaLactic Extragalactic All-sky MWA (GLEAM) survey operated by the Murchison Widefield Array (MWA) allows us to examine the relation and its frequency dependence with their 20 narrow bands at $72 - 231\,\mathrm{MHz}$. These examinations are important for ensuring the reliability of the radio SFR. In this study, we focus on 18 star-forming galaxies whose radio emission is detected by the GLEAM survey. These galaxies show that a single power-law fitting is valid for understanding how the relation between the radio and IR luminosities varies across MWA frequencies to $1.5\,\mathrm{GHz}$. We also investigate the consistency of the Star Formation Rate (SFR) calculated from the low-frequency emission with that from other indicators. Although this low-frequency emission has an advantage of the extinction-free indicator, the SFR calibration with averaged spectral parameters has a non-negligible uncertainty due to the variety of the radio to IR relation. We propose to use the individual spectral energy distribution for calculating the radio SFR for each star-forming galaxies with less uncertainty.

Acknowledgments

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Chapter 1

Introduction

ABSTRACT

Intro intro intro intro.

1.1 Tables

Chapter 2

Theoretical Background

ABSTRACT

Intro intro intro intro.

Here, I will describe synchrotron emissions?

Chapter 3

Data

ABSTRACT

In this chapter, I describe the dataset used for our study.

3.1 Herschel Reference Survey (HRS)

In this section, I introduce the Herschel Reference Survey (HRS) catalog [Boselli et al., 2010]. This survey is one of the Herschel guaranteed time key projects and originally it was compiled for understanding dust properties and interstellar medium in nearby galaxies. The catalog contains 322 galaxies selected with the three following criteria.

1. Volume-limitated:
   They choose galaxies whose distance from the earth is between 15 and 25 Mpc. This limitation reduce the distance uncertainty due to the galaxy peculiar motions and the selection effect due to the high-z galaxies. The lower limit (15 Mpc) also helps us to observe sources within the reasonable exposure time because galaxies too close to us are extended and we need too much time for the observation.

2. K-band selection:
   They choose galaxies whose 2MASS K-band total magnitudes are less than 12 mag for star-forming and peculiar galaxies (Sa-Sd-Im-BCD), and 8.7 mag for quiescent galaxies (E, S0, S0a). If there are galaxies whose K-band magnitude more than those values, their measurements are not regarded as an accurate photometry because of not enough exposure time. The reason why they have selected quiescent galaxies with the more stringent K-band selection criteria is these galaxies are expected to have low dust contents, and it is difficult to detect within the reasonable exposure time.

3. High galactic latitude:
   They choose galaxies whose galactic latitude is high enough to minimize the contamination from the galactic center ($b > +55°$). Also, they have selected galaxies with the low galactic extinction ($A_{\mathrm{B}} < 0.2$; Schlegel et al. 1998).

The selected galaxies located in the sky region between $10^{h}17^{m} < \text{R.A.}(2000) < 14^{h}43^{m}$ and $-6° < \text{decl.} < 60°$ (Figure 3.1) HRS galaxies spans a large range of the galaxy density environment from the center of Virgo cluster to the isolated region. As a definition, we can regard the HRS sample as a ideal one for studying the galaxy environment.

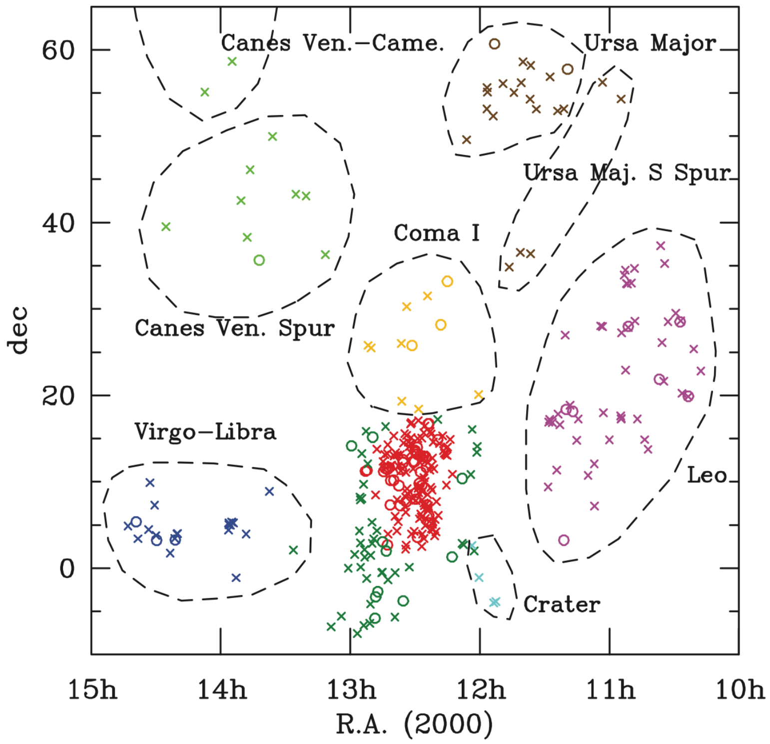

Figure 3.1: (Reprint from Boselli et al. 2010, Figure 1)
This figure shows the sky distribution of HRS galaxy samples. They show the early-type galaxies (E, S0, S0a) and late-type galaxies with circles and crosses, respectively. Dashed circles represents the different cloud regions. Each name of the cloud is shown close to each region. The red and dark green markers are Virgo galaxies (red: Virgo center, dark green: its outskirts).

In addition to a large range of the environment, the HRS galaxies distribute a wide range of the galaxy morphology (Figure 3.2).

Since HRS galaxies are supposed to be well-represented for the whole galaxy population located in the local universe, understanding their physical properties is a critical study. After Boselli et al. [2010] published the HRS sample, many studies investigating the physical properties for HRS galaxies have been done until now. Here, I introduce some of the studies for the HRS sample. Cortese et al. [2012] investigated their UV and optical properties using the Galaxy Evolution Explorer (GALEX; Martin et al. 2005) and SDSS-DR7 [Abazajian et al., 2009]. Boselli et al. [2014] studied their cold gas properties with ^{12}CO$\,(1-0)$ observed by the Kitt Peak 12m radio telescope and obtained from the literature data. They also investigate the HI gas obtained from The Arecibo Legacy Fast ALFA (ALFALFA; Giovanelli et al. 2005; Haynes et al. 2011) Survey. Ciesla et al. [2014] executed the SED fitting for HRS galaxies with Code Investigating GALaxy Emission (CIGALE; Noll et al. 2009).

Thanks to all of previous research about the HRS sample, they are well-studied among the wide range of the wavelength from the X-ray to the radio emission at 1.5 GHz. However, the low-frequency around 100 MHz is not examined so far. In this study, we focus on a subsample of HRS galaxies,

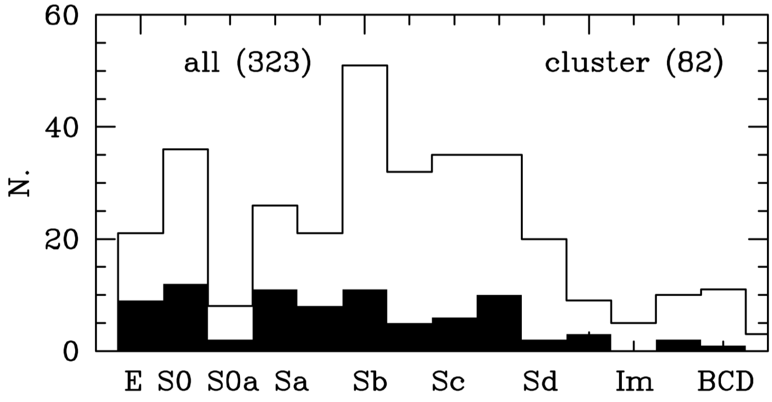

Figure 3.2: (Reprint from Boselli et al. 2010, Figure 2)
This figure shows the distribution in the morphology-type of HRS galaxies. The shaded histogram represents the distribution in it of only the cluster sample. Here, the cluster sample composed of HRS galaxies located in the Virgo A and B clouds.

whose counterpart is detected by the latest low-frequency survey (Section 3.2).

3.2 GLEAM survey

In this section, I introduce the GaLactic Extragalactic All-sky MWA (GLEAM) survey [Hurley-Walker et al., 2017]. This survey was operated by the Murchison Widefield Array (MWA) telescope [Tingay et al., 2013] in Western Australia. It observed a whole southern sky and a northern sky up to $+30^\circ$ ($\sim$25,000 deg^2; Figure 3.3). The catalog from this survey is a publicly-available and contains 307,455 detected radio sources with fluxes at 20 narrow bands between 72 and 231 MHz (each band has 7.68 MHz band width). The sensitivity and angular resolution at 200 MHz are $\sim$ 7 mJy and $\sim$ 2 arcmin respectively. The completeness of this survey at 200 MHz is 90% at $\sim$ 170mJy. Since this survey allows us to examine the low-frequency spectral energy distribution accurately with their 20 narrow bands, we adopt the radio source catalog for our study.

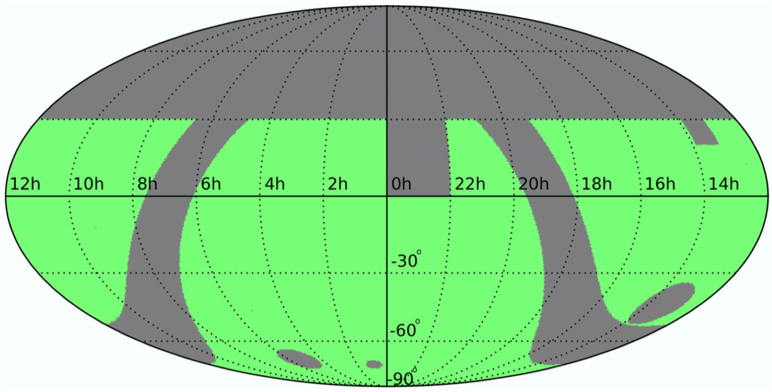

Figure 3.3: (Reprint from Hurley-Walker et al. 2017, Figure 11)
This figure shows the observed area by the GLEAM survey (green shaded region). They exclude several regions intentionally to minimize the contamination: Galactic plane (Absolute Galactic latitude $< 10°$), Ionospherically distorted ($0° <$ Dec $< +30°$ and $22^{\mathrm{h}} <$ R.A. $< 0^{\mathrm{h}}$), Centaurus A ($13^{\mathrm{h}}25^{\mathrm{m}}28^{\mathrm{s}}$ $-43°01'09''$, $r = 9°$), Sidelobe reflection of Cen A ($20° <$ Dec $< +30°$ and $13^{\mathrm{h}}07^{\mathrm{m}} <$ R.A. $< 13^{\mathrm{h}}53^{\mathrm{m}}$), Large Magellanic Cloud ($05^{\mathrm{h}}23^{\mathrm{m}}35^{\mathrm{s}}$ $-69°45'22''$, $r = 5.5°$) and Small Magellanic Cloud ($00^{\mathrm{h}}52^{\mathrm{m}}38^{\mathrm{s}}$ $-72°48'01''$, $r = 2.5°$).

Bibliography

Abazajian K. N., et al., 2009, The Astrophysical Journal Supplement Series, 182, 543

Boselli A., et al., 2010, Publications of the Astronomical Society of the Pacific, 122, 261

Boselli A., Cortese L., Boquien M., Boissier S., Catinella B., Lagos C., Saintonge A., 2014, Astronomy and Astrophysics, 564, 1

Ciesla L., et al., 2014, Astronomy & Astrophysics, 565, A128

Cortese L., et al., 2012, Astronomy & Astrophysics, 544, A101

Giovanelli R., et al., 2005, The Astronomical Journal, 130, 2598

Haynes M. P., et al., 2011, The Astronomical Journal, 142, 170

Hurley-Walker N., et al., 2017, Monthly Notices of the Royal Astronomical Society, 464, 1146

Martin D. C., et al., 2005, The Astrophysical Journal, 619, L1

Noll S., Burgarella D., Giovannoli E., Buat V., Marcillac D., Muñoz-Mateos J. C., 2009, Astronomy & Astrophysics, 507, 1793

Schlegel D. J., Finkbeiner D. P., Davis M., 1998, The Astrophysical Journal, 500, 525

Tingay S. J., et al., 2013, Journal of Physics: Conference Series, 440, 012033

Chapter 4

Methods

ABSTRACT

Intro intro intro intro.

Methods! Cross-matching, fitting, etc.

Chapter 5

Results

ABSTRACT

Intro intro intro intro.

Results

Chapter 6

Discussions

ABSTRACT

Intro intro intro intro.
Discussion!!

Chapter 7

Summary

ABSTRACT

Intro intro intro intro.

Summary or conclusions and future works.