Low-frequency GMRT Observations of Dusty Star-Forming Galaxies

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Abstract

The coldest and faintest dust component in molecular clouds dominates their dust masses, so understanding their cold dust content is necessary for understanding star formation in galaxies in general. To obtain accurate dust masses, we need to estimate the radio (thermal and non-thermal) components of the overlapping millimeter emission where dust emission dominates. To this end, we have carried out GMRT observations of four SPT- and IRAS-detected galaxies at frequencies between 310 and 1300 MHz, which we combine with SUMSS 843 MHz imaging. The radio fluxes were used to estimate the non-thermal spectral indices as well as star formation rates in our galaxy sample.

Searching for Cold Dust in Galaxies

Up to 90% of a galaxy's UV emission can be shifted to FIR wavelengths due to the presence of dust (Buat et al. 2010). The total dust emission from a galaxy reflects the chemical enrichment of ISM through accumulated episodes of star formation, and the galaxy's history of dust grain formation and the destruction (Dale et al. 2012).

FIR/submm emission from a star-forming galaxy is produced by multiple dust temperature components: cold ($\sim 15-25$ K), warm ($\sim 30-40$ K) and hot (T > 40 K). Cold dust, embedded in the dense molecular clouds, dominates the dust mass. Cold dust emission peaks in the mm/submm regime which also has a contribution free-free emission from HII regions and synchrotron emission from relativistic electrons. Massive stars ($M \geq 8M_\odot$) are responsible for both processes and hence radio emission is used to trace star-formation.

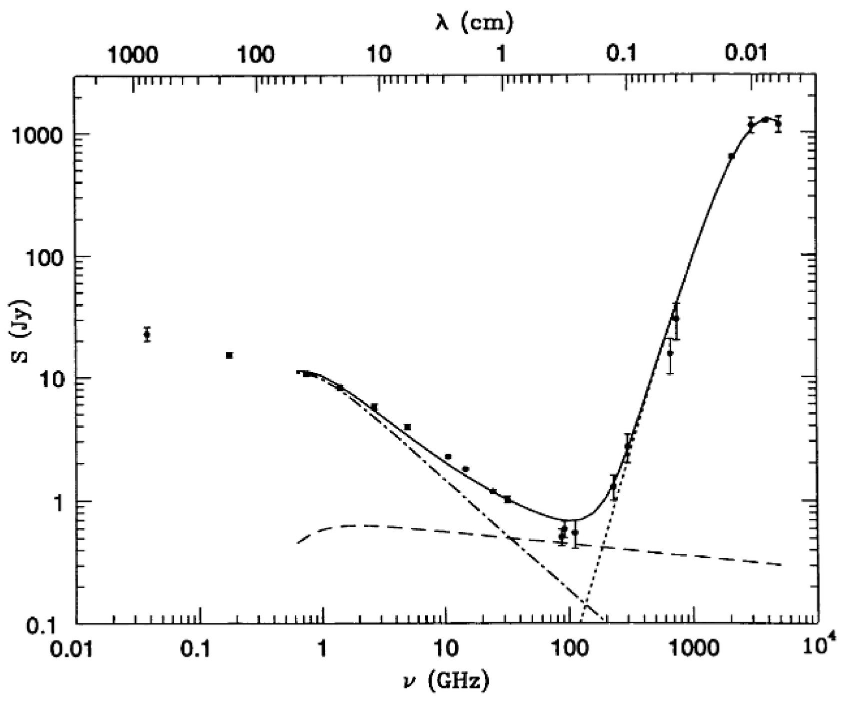

Figure 1: The observed radio/FIR spectrum of M82 is the sum (solid line) of synchrotron (dot-dash line), free-free (dashed line), and dust (dotted line) components (Condon 1992).

Usually, the radio spectra is modelled as the superposition of two power-laws (thermal and non-thermal emission):

$$S_{tot}(\nu) = S_{th}(\nu_0)\left(\frac{\nu}{\nu_0}\right)^{-0.1} + S_{nth}(\nu_0)\left(\frac{\nu}{\nu_0}\right)^{-\alpha_{nth}} \quad (1)$$

where α_{nth} is the spectral index of the synchrotron radiation spectrum. There have been various studies where the synchrotron spectra is curved, or has a break or an exponential decline (Williams & Bower 2010; Klein et al. 2018). **The slope of the non-thermal component thus plays an important role in order to obtain robust measurements of cold dust content in galaxies.**

Sample of Dusty Galaxies

To estimate cold dust content in nearby galaxies, South Pole Telescope (SPT) and Sydney University Molonglo Sky Survey (SUMSS) - detected galaxies, with known morphologies and redshifts, were selected based on the following criteria:

•They have flux densities $>$ 10 mJy in the 1.4 mm SPT band and spectral indices < 1.66 in the SPT bands.

•They are detected by IRAS at 60 and 100 μm and all four WISE bands. They have major axis diameters smaller than $5'$ in the WISE 22 μm maps.

The galaxies included in this work are listed in Table 1. All these galaxies are spirals and belong to the same Southern group of galaxies (Garcia 1993).

Table 1: Galaxies in this work

Galaxy	RA,Dec	z	Distance (Mpc)	Morphology	Activity Type
NGC 7496	23:09:47.29, -43:25:40.6	0.00550	19.35	SB(s)b	Seyfert 2
NGC 7590	23:18:54.81, -42:14:20.6	0.00526	18.26	SA(rs)bc	Seyfert 2
NGC 7599	23:19:21.14, -42:15:24.6	0.00551	19.30	SA(s)c	
IC 5325	23:28:43.43, -41:20:00.5	0.00501	17.22	SAB(rs)bc	

GMRT and UVIT Observations

GMRT observations at 325, 610 and 1300 MHz for the galaxies were taken in Dec 2017 and Jan 2018, and 610 MHz data was taken for NGC 7590, 7599 from the GMRT archive. 3C48, 3C138 and 3C147 were used for flux calibration. 2314−449 and 0010−418 were used as phase calibrators. The data reduction was done using AIPS (Astronomical Image Processing System).

Table 2: Summary of Data Reduction

Galaxy	Frequency (MHz)	Flux density (mJy)	RMS (μJy/beam)	Synthesized Beam	PA (deg)
NGC 7496	325	58.7	200	$21.44'' \times 10.28''$	5.91
	1300	21.4	28	$5.33'' \times 2.20''$	13.05
NGC 7590	325	131	800	$22.52'' \times 11.05''$	−3.37
	610	152	78	$10.86'' \times 4.94''$	12.54
NGC 7599	325	104	800	$22.52'' \times 11.05''$	−3.37
	610	129	78	$10.86'' \times 4.94''$	12.54
IC 5325	325	91	430	$19.60'' \times 9.01''$	−16.43
	610	66	38	$11.19'' \times 4.61''$	20.00
	1300	7*	64	$7.03'' \times 3.01''$	−14.45

*3σ limit, calculated from a circular region with a radius of $50''$.

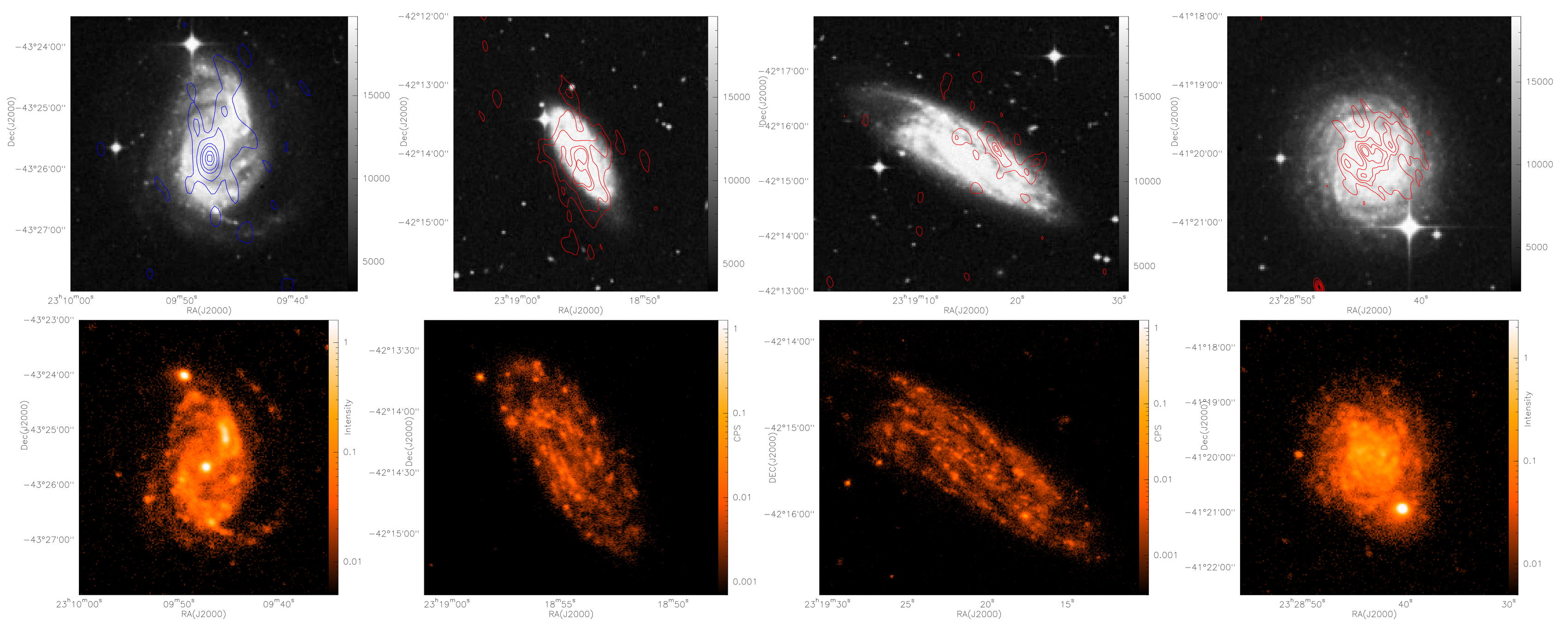

Figure 2: a) DSS image for NGC 7496 overlayed with 325 MHz contours. Contour levels are 1, 15, 35, 50, 75, 90 times σ where $\sigma = 200 \times 10^{-6}$ Jy/beam. b) DSS image for NGC 7590 overlayed with 610 MHz contours. Contour levels are 15, 25, 40, 45 times σ where $\sigma = 78 \times 10^{-6}$ Jy/beam. c) DSS image for NGC 7599 overlayed with 610 MHz contours. Contour levels are 2, 2.5, 4, 4.5 times σ where $\sigma = 800 \times 10^{-6}$ Jy/beam. d) DSS image for IC 5325 overlayed with 610 MHz contours. Contour levels are 8, 15, 20, 25, 30 times σ where $\sigma = 38 \times 10^{-6}$ Jy/beam. e) GALEX NUV image for NGC 7496. f) UVIT NUVB13 image for NGC 7590. g) UVIT NUVB13 image for NGC 7599. h) GALEX NUV image for IC5325.

To trace young stars and star-forming regions, galaxy UVIT observations were carried out for the NGC 7599 and NGC 7590 in November 2017 in FUV (F154W and F172M bands) and NUV (N245M and N279N bands).

Spectral Energy Distribution (SED) Modeling

SED modeling was done using CIGALE (Code Investigating Galaxy Emission). Using the models (1) Delayed star formation history 2) Bruzal & Charlot stellar emission 3) Nebular emission 4) Calzetti et al.(2000) Dust Attenuation Law 5) Draine & Li (2014) Dust emission 6) Radio emission 7) Fritz et al. (2006) AGN emission.), CIGALE builds theoretical SEDs and compares them to multi-wavelength observations of galaxies in order to derive the physical parameters for galaxies.

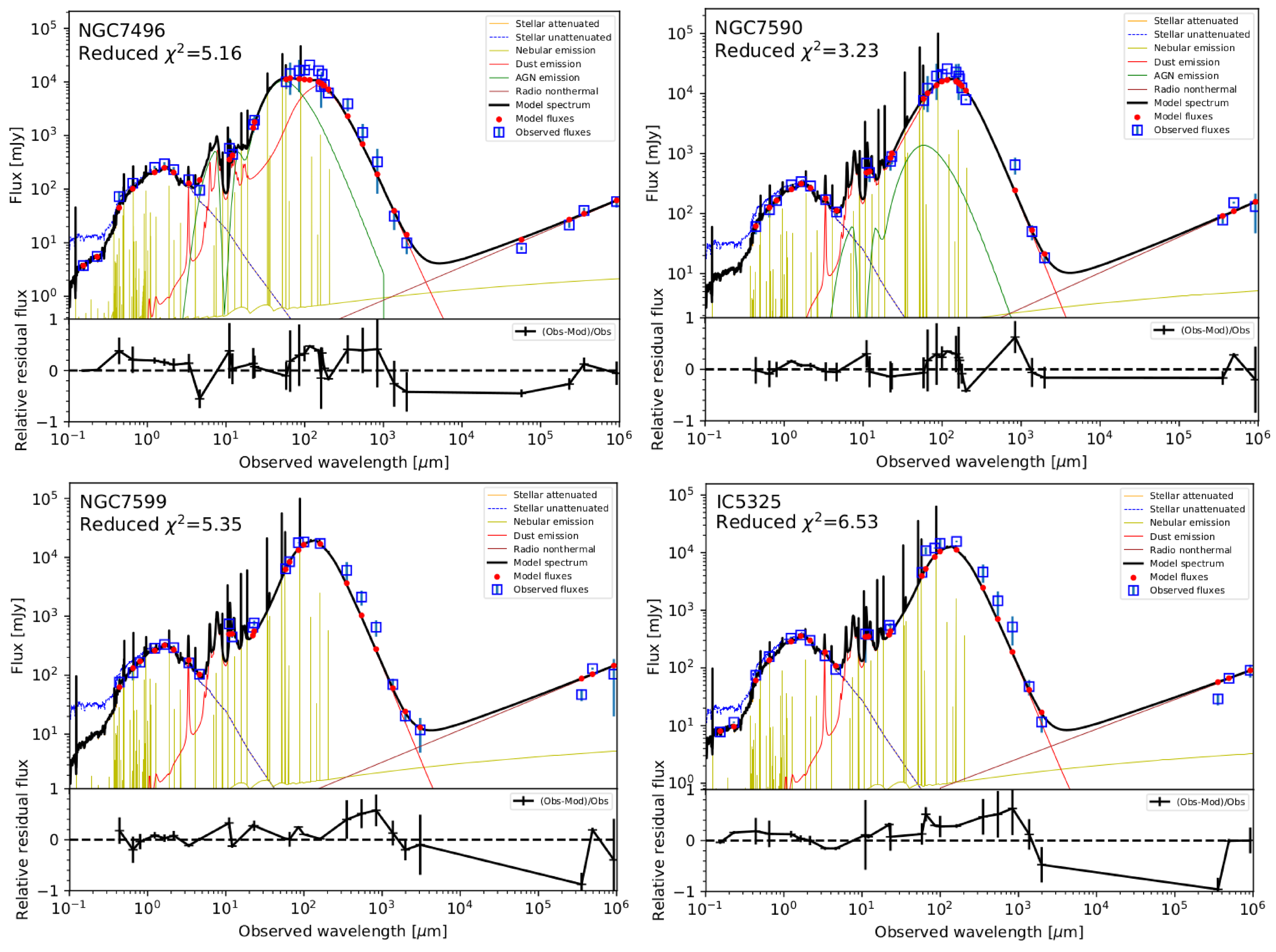

Figure 3: Best-fit CIGALE model to the SED of each galaxy using fluxes obtained from Planck HFI, GALEX, 2MASS, Johnson BRI, WISE, IRAS, SPT, SUMSS and GMRT observations.

Results

Distribution of Radio Emission

•**NGC 7496:** 1300 MHz emission is concentrated at the nucleus of the galaxy which is due to the presence of an AGN. The bright nucleus is also seen in the GALEX NUV image. While modeling the radio emission, the AGN contribution needs to considered which has not been done in this work.

•**NGC 7590:** Emission at 325 and 610 MHz is spread across the disc of the galaxy. It is a radio-quiet galaxy.

•**NGC 7599:** Very high flux density is seen in one spiral arm which outshines the entire galaxy. This could be due to the galaxy's interaction with its neighbour NGC 7599, resulting in triggered star-formation. This region is not as bright in the UVIT NUV image.

•**IC 5325:** Emission in 610 and 325 MHz was spread across the disk of the galaxy. The galaxy was not detected at 1300 MHz.

Outcome of SED Modeling

The galaxies have dust masses and luminosities similar to those of actively star forming galaxies (Kwan & Xie 1992; Calzetti et al. 2000).

Table 3: Fitted and Calculated parameters from the SEDs

Galaxy	Dust Mass 10^7 M$_\odot$	Dust Luminosity 10^{10} L$_\odot$	AGN Torus Luminosity 10^{10} L$_\odot$	Radio Spectral Index
NGC 7496	2.48	0.58	1.44	-0.6 ± 0.10
NGC 7590	2.44	1.43	0.17	-0.6 ± 0.13
NGC 7599	2.99	1.55	-	-0.5 ± 0.19
IC 5325	1.72	0.85	-	-0.5 ± 0.53

Star Formation Rates (SFRs)

Table 4: SFRs for the galaxies

Galaxy	IRAS 60μm flux density (Jy)	SFR^a (M$_\odot$ yr^{-1})	GMRT 610 MHz flux density (mJy)	SFR^b (M$_\odot$ yr^{-1})
NGC 7496	10.1	1.88	-	-
NGC 7590	7.69	1.32	152	1.72
NGC 7599	6.39	1.22	129	1.60
IC 5325	4.53	0.69	66	0.67

^{a} Rowan-Robinson et al. (2008) ^{b} Garn et al. (2009)

SFR for Milky way is 1.9 ± 0.5M$_\odot$ yr^{-1} and for nearby spiral galaxies can go up to 2.8M$_\odot$ yr^{-1} (Chomiuk & Povich, 2011). The SFRs for the galaxies suggest that all these galaxies are normal star-forming spirals. For NGC 7599, the anomalous star-forming region has a SFR of ~ 0.15M$_\odot$ yr^{-1}.

References

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